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WIRELESS LOCAL AREA NETWORKS: SIMULATION AND ANALYSIS

by

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Wireless communication is currently in a state of rapid evolution. This evolution is driven by the numerous advantages of the wireless networks. One major constraint to this evolution is the lack of standardization. Also a major concern are the interference problems of the signal at the reception point caused by the multiple paths that the electromagnetic waves travel (multi-path interference).

This thesis presents two separate simulations. In the first, a realistic physical model of a wireless local area network is developed. In this simulation, the multi-path interference at the reception point is investigated. The results of this physics-based simulation are used to assess an important assumption in the second simulation.

In the second simulation, we examine the reliability of the wireless standard for the medium access control (MAC) layer, using CACI COMNET III network simulation software. This standard was published in 1997, by the IEEE's working group 802.11 and in this thesis is tested and analyzed under different network loads. One major result is that the optimum load for a five working stations wireless LAN, is from 80 to 200 packets per second. Below that load range the channel utilization is small and above that the network is overloaded.

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WIRELESS LOCAL AREA NETWORKS: SIMULATION AND ANALYSIS

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Wireless communication is currently in a state of rapid evolution. This evolution is driven by the numerous advantages of the wireless networks. One major constraint to this evolution is the lack of standardization. Also a major concern are the interference problems of the signal at the reception point caused by the multiple paths that the electromagnetic waves travel (multi-path interference).

This thesis presents two separate simulations. In the first, a realistic physical model of a wireless local area network is developed. In this simulation, the multi-path interference at the reception point is investigated. The results of this physics-based simulation are used to assess an important assumption in the second simulation.

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I. INTRODUCTION

Wireless communications is currently in a state of rapid evolution. This evolution is driven by the numerous advantages of wireless networks over the traditional wired ones. Previously, a major constraint to this evolution was the lack of standardization. In 1997 the IEEE's working group 802.11, after years of research, published a standard for wireless local area networks. This standard provides the guidelines for both physical and medium access control (MAC) layers.

This research focuses on the development of a wireless local area network on which the new standard is applied and tested. In the physical layer, a model of a transmitter and a receiver system is used to demonstrate the signal strength problems caused by multipath interference. This model investigates the worst case signal-to-noise ratio in the receiver, created by the interference of two waves transmitted from a point source. The first one travels on a straight line connecting the transmitter and the receiver and the second arrives at the reception point after reflection. In the medium access layer, a simulation of a wireless local area network investigates the behavior of the new standard's protocol, under different network loads.

The objective of this thesis is to propose a realistic and applicable physical model, that can be used in a wireless local area network and to investigate the reliability of such a network, by implementing the IEEE 802.11 CSMA/CA MAC protocol. For the thesis purposes, this stand-alone local area network consists of five working stations, operating outdoors in a separation distance of approximately 100 meters.

A. SCOPE OF THE THESIS

To serve the thesis objectives, this research is divided into two separate, but closely related tasks. Starting with empirical expressions for irradiance and using the basic reflection principles and other fundamental concepts of optics, we derive a formula that calculates the irradiance at a point in space. This is the point where the two electromagnetic waves arrive, as they travel the two different paths mentioned above. The irradiance, is given as a function of the distances traveled by the two waves, the atmospheric attenuation and the reflectivity of the

bouncing surface. Then, by comparing this combined irradiance with the dual-path irradiance, we create a worst case of signal strength. The ratio of the irradiances in these two cases corresponds to the signal-to-noise ratio (SNR) at the reception point. From this, we can determine if the standardized link capacity proposed by the IEEE's 802.11 CSMA/CA protocol is applicable and what the bandwidth of a receiver should be, in order to account for the worst case signal-to-noise ratio.

Secondly, with the use of the CACI COMNET III software package, we test the performance of the CSMA/CA under different loads. For this purpose we simulate a wireless local area network. The worst case signal-to-noise ratio and the propagation delay found on the first part of the thesis are used as inputs for the simulation of the wireless network. In order to make conclusions as far as the applicability of the protocol is concerned, we focus in two major simulation result categories. Firstly on the channel utilization which is a way to measure the reliability of the network. Channel utilization provides information about the network's congestion and shows if the link is stable and adequate for the communications between the working stations. Secondly, we focus on the packet transmission delay caused by the constantly increasing number of packets in the network. This delay is another way to estimate the network's performance.

B. THESIS ORGANIZATION

The thesis consists of eight chapters. Chapter II gives some basic background information about the history, evolution and importance of wireless communications. Moreover, this chapter briefly describes the various types of wireless communications. Chapter III examines the transport of energy in space, by the electromagnetic waves. As part of that, we present the concept of irradiance. Then we attempt to derive a set of multiple-path interference relationships that we use for the simulation of the transmitter-receiver system. Chapter IV describes the model the parameters and the results of this simulation. Chapter V presents a theoretical background on wireless networks, their evolution and their constraints. Furthermore, several advantages and design considerations of the wireless networks are described. In Chapter VI, a brief description of the network simulation software, the COMNET III, is given. We examine the capabilities of the software and the different

presentations of the results. Chapter VII describes the model for the simulation, the different loads, the values of the parameters used for the CSMA/CA, the description of the output reports and finally the simulation results. Chapter VIII concludes the thesis with a research review and suggestions for future work.

II. WIRELESS COMMUNICATIONS

A. INTRODUCTION

Our age has given rise to an increasing demand by people to be on-line. For mobile users, twisted pair, coaxial cable and even fiber optics are of no use. They constantly need to get updated data for their laptop, notebook, palmtop, or wristwatch computers without being restricted by the terrestrial communication infrastructure. For this type of user, wireless communication in general, is the only solution since it has many important applications.

Wireless also has advantages for even fixed devices in some circumstances. For example, wireless may be preferable to a fiber for areas with physical obstacles, such as mountains, rivers, seas, etc. It is noteworthy that modern wireless digital communication began in the Hawaiian Islands, where large chunks of Pacific Ocean separated the users and the telephone system was inadequate.

B. THE ELECTROMAGNETIC SPECTRUM

When electrons accelerate, they create electromagnetic waves that propagate through free space (see Ch III). These waves were predicted by the British physist James Clerk Maxwell in 1865 and first produced and observed by the German physicist Heinrich Hertz in 1887. The number of oscillations per second of an electromagnetic wave is called its *frequency*, f, and is measured in Hz (in honor of Heinrich Hertz). The distance between two consecutive maxima (or minima) is called the *wavelength*, which is universally designated by the Greek letter λ (lambda).

By attaching an antenna of the appropriate size to an electrical circuit, the electromagnetic waves can be broadcast efficiently and received by a receiver some distance away. All wireless communication is based on this principle. In vacuum, all electromagnetic waves travel at the same speed, no matter what their frequency. This speed, usually called the *speed of light*, c, is approximately 3×10^8 m/sec. In copper or fiber the speed slows to about 2/3 of this value and becomes slightly frequency dependent. The speed of light is the ultimate speed limit. No object or signal can ever move faster than it.

The fundamental relation between f, λ, and c (in vacuum) is

$$\lambda f = c \tag{2.1}$$

Since c is a constant, knowledge of f can be used to find λ and vice versa. For example, a 1 MHz wave is about 300 meters long and 1-cm waves have a frequency of 30 GHz.

The electromagnetic spectrum is shown in Figure 2-1. The radio, microwave, infrared, and visible light portions of the spectrum can all be used for transmitting information by modulating the amplitude, frequency, or phase of the waves. Ultraviolet light, X-rays, and gamma rays would be even better, due to their higher frequencies, but they are hard to produce and modulate, do not propagate well through buildings, and can be harmful to people. The bands listed at the bottom of Figure 2-1 are based on the wavelengths. For example, the LF band goes from 1 km to 10 km (approximately 30 kHz to 300 kHz). The terms LF, MF, and HF refer to low, medium, and high frequency, respectively. Clearly, when the names were assigned, little thought was given to operating at frequencies above 10 MHz, so the higher bands were named the Very, Ultra, Super, Extremely, and Tremendously High Frequency bands. The amount of information that an electromagnetic wave can carry is related to its bandwidth. With current technology, it is possible to encode a few bits per Hertz at low frequencies, but often as many as 40 under certain conditions at high frequencies, so a cable with a 500 MHz bandwidth can carry several gigabits per second.

If we solve Equation 2.2 for f and differentiate with respect to λ we get

$$\frac{df}{d\lambda} = -\frac{c}{\lambda^2} \tag{2.2}$$

Converting this equation to finite differences instead of differentials and only for absolute values, it becomes

$$\Delta f = \frac{c\Delta\lambda}{\lambda^2} \tag{2.3}$$

Thus, given the width of a wavelength band, $\Delta\lambda$, we can compute the corresponding frequency band, Δf , and from that the data rate the band can produce. The wider the band, the higher the data rate.

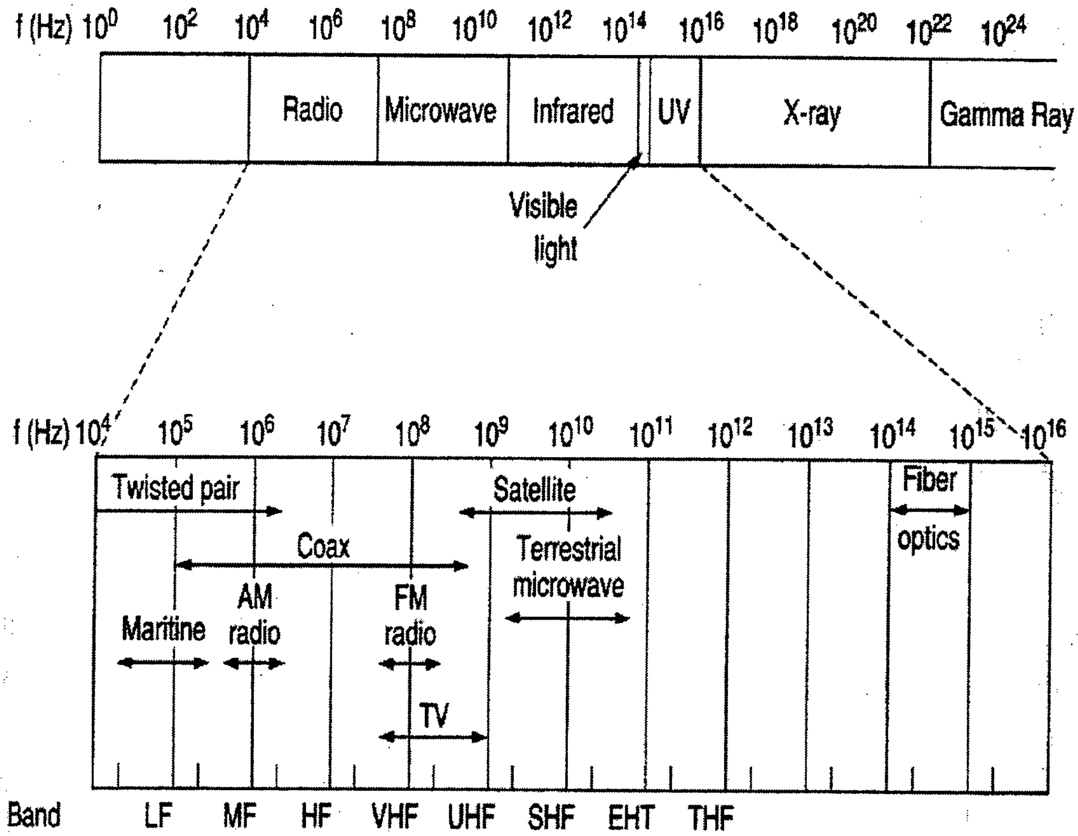

Figure 2.1 The electromagnetic spectrum and its uses for communication

To prevent radio interference from the many users, there are national and international agreements about who gets to use which frequencies. Since everyone wants a higher data rate, everyone wants more spectral bandwidth. In the United States, the FCC[1] allocates spectrum

[1] FCC: Federal Communications Commission.

for AM and FM radio, television, and cellular phones, as well as for telephone companies, police, maritime, navigation, military, government, and many other competing users. Worldwide, an agency of ITY-R[2] (WARC)[3] does this work. Table 2.1 gives an analytic description of the use of different frequencies of the electromagnetic spectrum.

Most transmissions use a narrow frequency band (i.e., $\Delta f / f \leq 1$) to get the best reception. However, in some cases, the transmitter hops from frequency to frequency in a regular pattern or the transmissions are intentionally spread out over a wide frequency band. This technique is called *spread spectrum*. It is very useful for military communication because it makes transmissions hard to detect and practically impossible to jam. Another spread spectrum technique, more commonly used in the commercial world is *the direct sequence spread spectrum*.

Table 2.1 Electromagnetic Spectrum Use

Frequencies	Designation	Services/Uses/EM Phenomena
3-30 KHz	Very Low Frequency	Navigation , Sonar, Submarine communications
30-300 KHz	Low Frequency	Radio Beacons, Navigational Aids
300-3000 KHz	Medium Frequency	535-1605 KHz : AM Radio Coast Guard Communications, Direction Finding
3-30 MHz	High Frequency	Telephone, Telegraph, Facsimile 3-26 MHz: Short Wave Radio Amateur Radio, CB, Ship-to-coast communications
30-300 MHz	Very High Frequency	54-216 MHz: VHF TV, FM Radio Air Traffic Control, Police, Taxicab

[2] ITY-R: International Telecommunication Union (Radiocommunicatios sector).

[3] WARC: World Administrative Radio Conference.

300-3000 MHz	Ultra High Frequency	476-806 MHz: UHF TV Satellite Comms Surveillance Radar
3-30 GHz	Super High Frequency	Airborne Radars, Microwave Links, satellite Comms
30-300 GHz	Extremely High Frequency	Radars, Experimental Band
10^3-10^4 GHz	Infrared Radiation	Photography
10^5-10^6 GHz	Visible Light	Human Vision
10^6-10^8 GHz	Ultraviolet Radiation	Sterilization
10^8-10^9 GHz	X-rays	X-ray Examination
10^{10}-10^{13} GHz	Gamma Rays	Cancer Therapy
10^{14}-	Cosmic Rays	Astronomy, Physics

C. RADIO TRANSMISSION

Radio waves are easy to generate, can travel long distances, and penetrate buildings easily, so they are widely used for communication, both indoors, and outdoors. Radio waves also are omnidirectional, meaning that they travel in all directions from the source, so that the transmitter and receiver do not have to be carefully aligned physically.

The properties of radio waves are frequency dependent. At low frequencies, radio waves pass through obstacles well, but the power falls off sharply with distance from the source, roughly as $1/r^3$ in air. At high frequencies, radio waves tend to travel in straight lines and bounce off obstacles. They are also absorbed by rain. At all frequencies, radio waves are subject to interference from motors and other electrical equipment. Due to the ability of radio waves to travel long distances, interference between users is a major problem. For this reason, all governments tightly license the users of radio transmitters.

In the VLF, LF, and MF bands, radio waves follow the ground, as illustrated in Figure 2.2. These waves can be detected for more than 1000 km at the lower frequencies, less at the higher ones. AM radio broadcasting uses the MF band. Radio waves in these bands easily pass through buildings, which is why portable radios work indoors. The main problem with using

these bands for data communication is the relatively low bandwidth they offer, as shown in Equation 2.3.

In the HF and VHF bands, the ground waves tend to be absorbed by the earth. However, the waves that reach the ionosphere, a layer of charged particles circling the earth at a height of 100 to 500 km, are refracted by it and sent back to earth, as shown in Figure 2.3. Under certain atmospheric conditions, the signals may bounce several times. The military communicates in the HF and VHF bands.

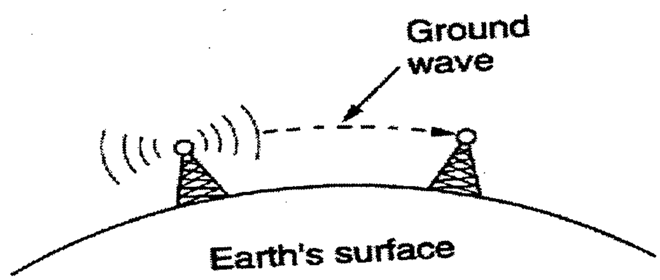

Figure 2.2 VLF, LF and MF Bands

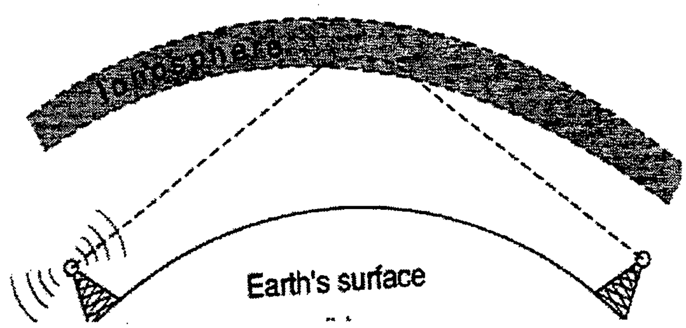

Figure 2.3 HF Band

D. MICROWAVE TRANSMISSION

Above 100 MHz, the waves travel predominantly in straight lines and can therefore be narrowly focused. Concentrating all the energy into a small beam using a parabolic antenna (like the familiar satellite TV dish) gives a much higher signal-to-noise ratio. Therefore, the transmitting and receiving antennas must be accurately aligned with each other. In addition, this directionality allows multiple transmitters lined up in a row to communicate with multiple receivers in a row without interference. Although they are now being replaced by fiber optics, these microwaves formed the heart of the long-distance telephone transmission system for decades.

Since microwaves travel in a straight line, the earth will obstruct towers that are too far apart. Consequently, repeaters are needed periodically. The higher the towers are, the further apart they can be. The distance between repeaters goes up roughly with the square root of the tower height. For example, given 100-m high towers, repeaters can be spaced 80 km apart.

Unlike radio waves at lower frequencies, microwaves do not pass through buildings well. Moreover, even though the beam may be well focused at the transmitter, there is still some divergence in space. Some waves may be refracted by low-lying atmospheric layers and may take slightly longer to arrive than direct waves. The delayed waves may arrive out of phase with the direct wave and thus cancel the signal. This effect is called *multipath fading* and is often a serious problem. This phenomenon is weather and frequency dependent. Some operators keep 10 percent of their channels idle as spares to switch to when multipath fading wipes out some frequency band temporarily.

The demand for more spectrum is a strong force to improving the technology so transmissions can use still higher frequencies. Bands up to 10 GHz are now in routine use. Above about 8 GHz another serious problem arises: Absorption by water. Waves at these frequencies are only a few centimeters long and are absorbed by rain, adding a new consideration in communications. As with multipath fading, the only solution is to shut off links that are being rained on and re-route them.

In addition to being used for long distance transmission, microwaves have another important use, namely, the *Industrial/Scientific/Medical* bands. These bands form the one exception to the licensing rule: transmitters using these bands do not require government

licensing. One band is allocated worldwide: 2.400 - 2.484 GHz. In addition, in the United States and Canada, bands also exist from 902-928 MHz and from 5.725-5.850 GHz. These bands are used for cordless telephones, garage door openers, wireless hi-fi speakers, security gates, etc. The 900 MHz band works best but is crowded and equipment using it may only be operated in North America. The higher hands require more expensive electronics and are subject to interference from microwave ovens and radar installations. Nevertheless, these bands are popular for various forms of short-range wireless networking because they avoid the problems associated with licensing.

To sum up, microwave communication is widely used for long-distance telephone communication, cellular telephones, television distribution, and other uses, that a severe shortage of spectrum has developed.

E. INFRARED AND MILLIMETER WAVE TRANSMISSION

Unguided infrared and millimeter waves are widely used for short-range communication. The remote controls used on televisions, VCRs and stereos all use infrared communication. They are relatively directional, cheap, and easy to build, but have a major drawback: they do not pass through solid objects. In general, as we go from long-wave radio to visible light, the waves behave more and more like light and less like radio.

On the other hand, the fact that IR waves do not pass through solid walls could be also considered a plus: An IR system in one room of a building will not interfere with a similar system in adjacent rooms. Furthermore, security of infrared systems against eavesdropping is better than that of radio systems precisely for this reason. Therefore, no government license is needed to operate an IR system.

These properties have made IR systems useful for indoor wireless LANs. Infrared communication cannot be used outdoors, because the sun shines as brightly in the infrared as in the visible spectrum.

F. LIGHTWAVE TRANSMISSION

Unguided optical signaling has been in use for millennia. A recent application is to connect the LANs in two buildings via lasers mounted on their rooftops. Coherent optical

signaling using lasers is inherently unidirectional, so each building needs its own laser and its own photodetector. This scheme offers very high bandwidth and very low cost. It is also rather easy to install and unlike microwave, does not require a FCC license.

A disadvantage is that laser beams cannot penetrate rain or thick fog but they normally work well on sunny days. Another potential problem is the heat from the sun: In a sunny day, the heat can cause convection currents to rise up from the roof of the building and the resulting turbulence may divert the beam. Thus focusing the beam can be a difficult task. Figure 2.4 shows how convection currents can interfere with laser communication systems.

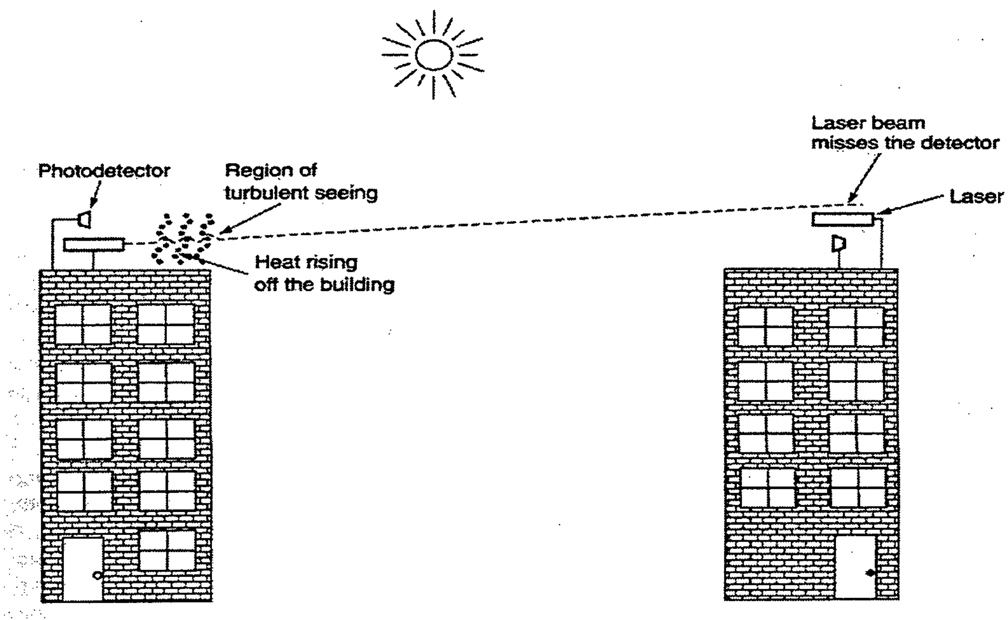

Figure 2.4 Convection currents interference with laser communications

III. INTERFERENCE OF ELECTROMAGNETIC WAVES

In this chapter we discuss the transport of energy by electromagnetic waves. Furthermore, we introduce the quantity of radiant flux density or Irradiance as a way of measuring this energy. Finally, we examine the interference caused by the addition of two waves of the same frequency.

A. REFLECTION AND REFRACTION OF E/M WAVES

Energy is carried from a source by electromagnetic (E/M) radiation, either directly through free space, or indirectly by refraction or/and reflection. This radiated energy is transported through space by electromagnetic waves. These waves are propagated by alternating their electric and magnetic field components, which lie on two mutually orthogonal planes, as shown in Figure 3.1.

The relationship between the wavelength λ and the frequency f is given by Euation 2.1, or solving for λ, gives

$$\lambda = \frac{c}{f} \tag{3.1}$$

When an electromagnetic wave hits a material surface in general, it is reflected and refracted, as shown in Figure 3.2 and Figure 3.3.

When an electromagnetic wave penetrates matter, its velocity changes according to the index of refraction n of the material. This refractive index is the ratio of the velocity of light in a vacuum to the velocity of light in the medium,

$$n = \frac{c}{u} \tag{3.2}$$

Since the frequency remains constant, the wavelength changes, upon the interaction with the material. This causes the bending shown in Figures 3.2 and 3.3.

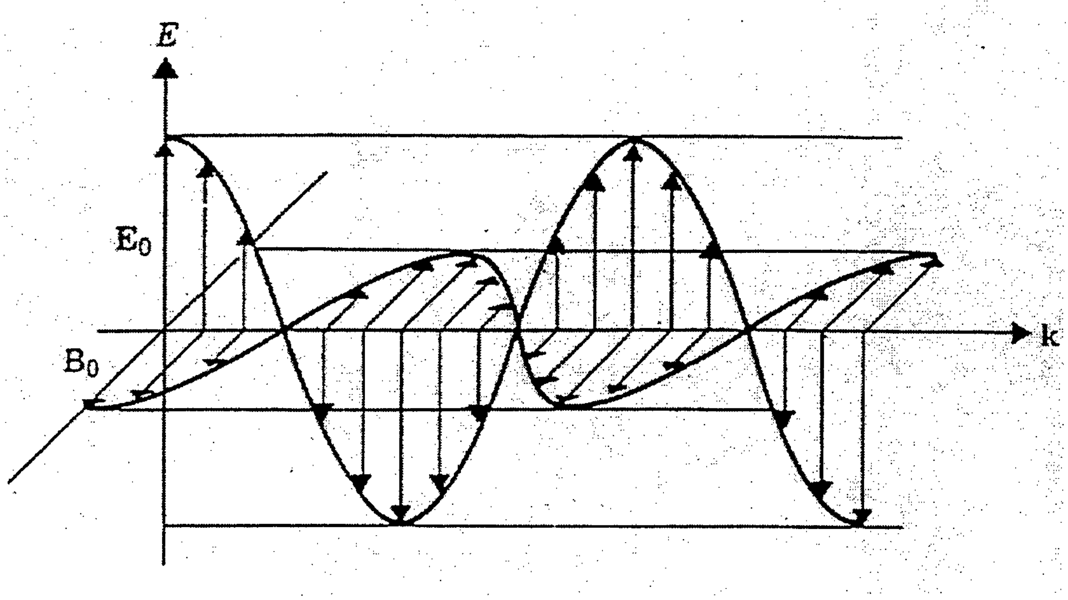

Figure 3.1 Electromagnetic Wave

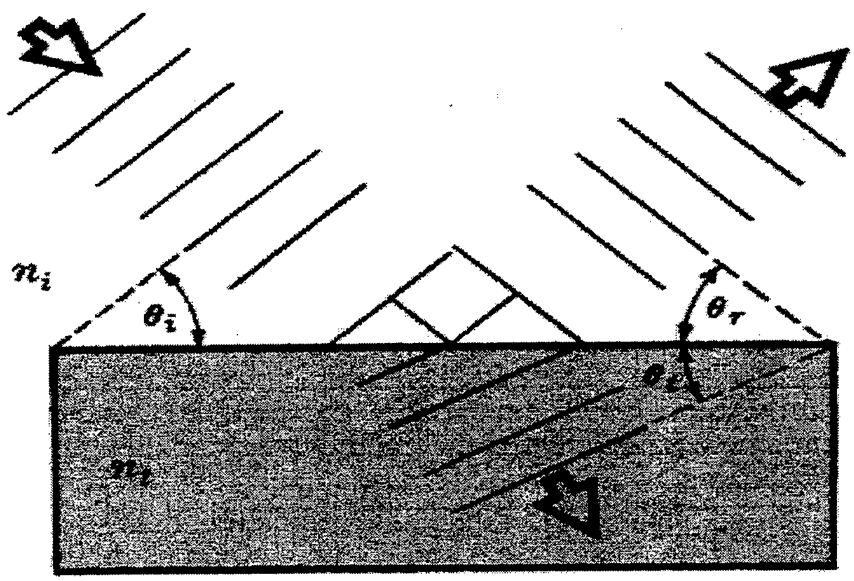

Figure 3.2 Reflection and Refraction of E/M wave

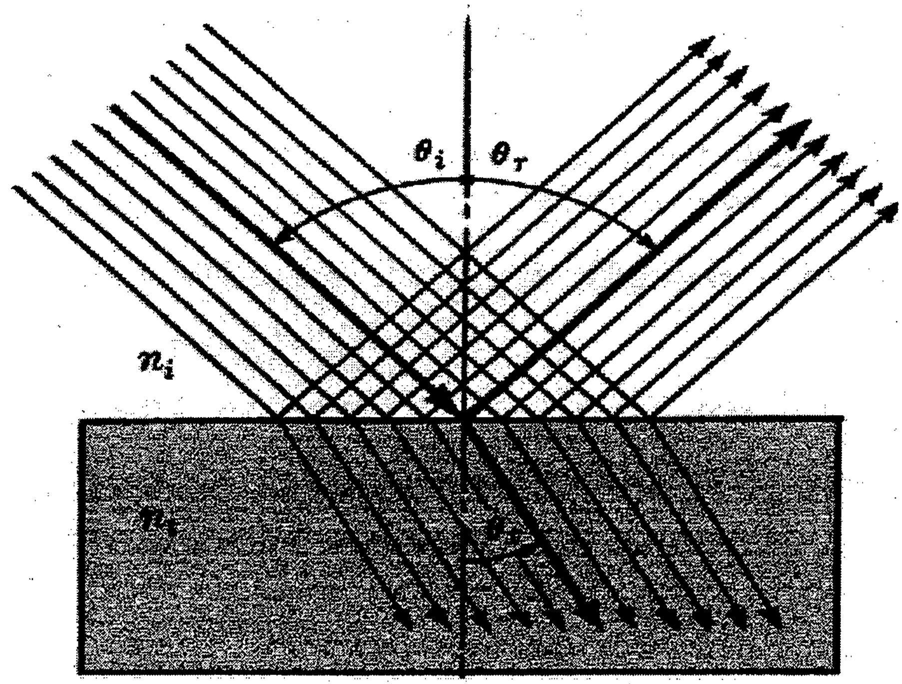

Figure 3.3 Reflection and Refraction. Associated ray diagram

The three basic laws of reflection and refraction are as follows:

(1) The incident, reflected and transmitted rays all reside in a plane, known as the plane of incidence, which is normal to the interface.

(2) The angle of incidence equals the angle of reflection, or

$$\theta_i = \vartheta_r = \theta_1 \tag{3.3}$$

(3) Snell's law relates the incident and transmitted ray directions:

$$n_1 \cdot \sin\theta_1 = n_2 \cdot \sin\theta_2 \tag{3.4}$$

Where n_1 is the index of refraction of the medium or material 1, θ_1 is the angle of incidence, measured from the normal to the surface, n_2 is the index of refraction of the medium or material 2 and θ_2 is the angle of refraction, measured from the normal.

Furthermore, there are two sets of relations that are completely general and apply to any linear, isotropic, homogeneous media: The Fresnel Equations. These equations relate all the parameters mentioned above and their derivation is beyond the scope of this thesis. The Fresnel relations are two sets of equations, as follows:

1. **The Electric field is perpendicular to the plane of incidence**

$$r_{\perp} = \frac{n_i \cos\theta_i - n_t \cos\theta_t}{n_i \cos\theta_i + n_t \cos\theta_t} \tag{3.5}$$

$$t_{\perp} = \frac{2n_i \cos\theta_i}{n_i \cos\theta_i + n_t \cos\theta_t} \tag{3.6}$$

Where $r_{\perp}$ is the amplitude reflection coefficient and $t_{\perp}$ is the amplitude transmission coefficient.

2. **The Electric field is parallel to the plane of incidence**

$$r_{\Uparrow} = \frac{n_t \cos\theta_i - n_i \cos\theta_t}{n_i \cos\theta_t + n_t \cos\theta_i} \tag{3.7}$$

$$t_{\Uparrow} = \frac{2n_i \cos\theta_i}{n_i \cos\theta_t + n_t \cos\theta_i} \tag{3.8}$$

Where $r_{\Uparrow}$ is the amplitude reflection coefficient and $t_{\Uparrow}$ is the amplitude transmission coefficient.

B. ELECTROMAGNETIC ENERGY TRANSPORT

As we have seen, one of the most significant properties of the electromagnetic wave is that it transports energy. An electromagnetic field occupies some region of space and it is

natural to consider the radiant energy per unit volume, or *the energy density, u*. For the electric field alone, the energy density, u_E, is

$$u_E = \frac{E^2 \varepsilon_0}{2} \qquad (3.9)$$

Where E is the amplitude of the electric field and ε_0 is the electric permittivity of the free space, given by $\varepsilon_0 = 8.8542 \ 10^{-12}$ $[C^2 N^{-1} m^{-2}]$. Conceptually, the permittivity embodies the electrical behavior of the medium. In a sense, it is a measure of the degree to which the material is permeated by the electric field in which it is immersed.

Similarly, the energy density in a magnetic field, u_B, is

$$u_B = \frac{B^2}{2\mu_0} \qquad (3.10)$$

Where B is the amplitude of the magnetic field and μ_0 is the magnetic permeability of the free space, defined in an analogous way and it is:

$$\mu_0 = 4\pi 10^{-7} \quad [N\,s^2\,C^{-2}]$$

For a plane wave we know that E=cB and for the speed of light, c, it is known

$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \qquad (3.11)$$

From Equations 3.9, 3.10, 3.11 follows that

$$u_E = u_B \qquad (3.12)$$

The energy travelling through space in the form of an electromagnetic wave is shared between the constituent electric and magnetic fields. Since

$$u = u_E + u_B \tag{3.13}$$

it is obvious that

$$u = \varepsilon_0 E^2 \tag{3.14}$$

and

$$u = \frac{B^2}{\mu_0} \tag{3.15}$$

To represent the flow of the electromagnetic energy, let S be the symbol for the transport of energy per unit time across a unit area. It has units of [W/m^2]. During the very small time interval Δ t, only the energy contained in the cylindrical volume, u(c Δ t A), will cross the area A. hence,

$$S = \frac{uc\Delta tA}{\Delta tA} = uc \tag{3.16}$$

And by combining Equations 3.11, 3.14, 3.15 gives

$$S = \frac{1}{\mu_0} EB \tag{3.17}$$

Now we assume that for isotropic media, the energy flows in the direction of propagation of the wave. The corresponding vector S is

$$\mathrm{S} = \frac{1}{\mu_0} \mathrm{ExB} \tag{3.18}$$

Which by using the Equation 3.7 can be written

$$S=c^2 \varepsilon_0 \ ExB \tag{3.19}$$

The magnitude of this vector is the power per unit area crossing a surface whose normal is parallel to S. This vector is known as the Poynting vector (after J.H.Poynting).

Now we consider the case of a harmonic, linearly polarized plane wave, traveling through free space in the direction of k. The equation of the wave is:

$$E=E_0\cos(\vec{k}\cdot\vec{r}\text{ -wt}) \tag{3.20}$$

Where E_0 is the wave's amplitude and using the Equation 3.19,

$$S=c^2 \varepsilon_0 \ ExB\cos^2(\vec{k}\cdot\vec{r}\text{ -wt}) \tag{3.21}$$

The term ExB, cycles from maxima to minima. The change is so rapid that an instantaneous value of S would be impractical. Therefore we will implement a time averaging procedure. The time averaged value of the magnitude of the Poynting vector, $\langle S \rangle$, is a measure of the quantity known as the *irradiance*, or *radiant flux density* "*I*". A graphical representation of the concept of irradiance is given in Figure 3.4.

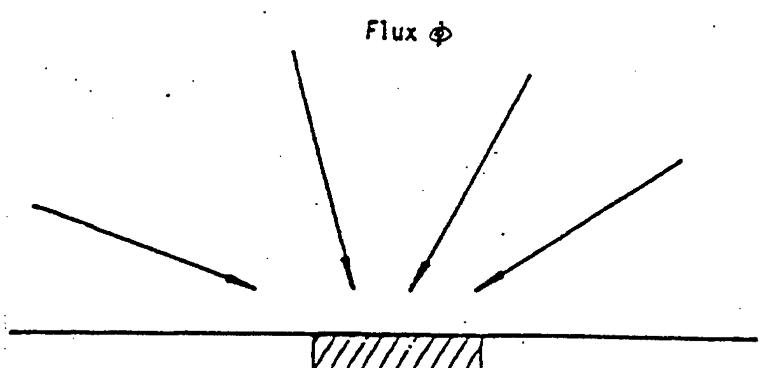

Figure 3.4 The concept of Irradiance

In this case, the time integral of the term $\cos^2(\vec{k}\cdot\vec{r}$ -wt), over a period T, will be:

$$\int_{t}^{t+T} \cos^2(\vec{k}\cdot\vec{r} - wt)dt' = \frac{1}{2} \tag{3.22}$$

Hence

$$\langle S \rangle = \frac{c^2\varepsilon_0}{2}\left|\vec{E}_0 \times \vec{B}_0\right| \tag{3.23}$$

or

$$I \equiv \langle S \rangle = \frac{c\varepsilon_0}{2}E_0^2 \tag{3.24}$$

Therefore, <u>the irradiance is proportional to the square of the amplitude of the electric field.</u>

C. ADDITION OF WAVES OF THE SAME FREQUENCY

A solution of the differential wave equation can be written in the form:

$$E(x,t) = E_0 \sin(wt - (kx + \varepsilon)) \tag{3.25}$$

Where the magnitude of the wave (E) is given as a function of both space (x) and time (t). E_0 is the amplitude of the wave propagating along the positive x-axis. Let $a(x, \varepsilon) = -(kx + \varepsilon)$. Now 3.25 becomes

$$E(x,t) = E_0 \sin(wt + a(x,\varepsilon)) \tag{3.26}$$

Let's assume we have two such waves which travel from a point source A to a reception point B. The first one, E_1, travels along a hypothetical straight line which connects

the two points and is known as the Line of Sight (LOS). The second one, E_2, bounces off an infinite wall which is parallel to the LOS in some distance from points A and B. This system is described in the following chapter and it is shown Figure 4.1. Now,

$$E_1 = E_A \sin\left(wt - kd_1\right) \tag{3.27}$$

Where

$$E_A = \frac{Eo\exp(-\alpha d_1)}{d_1} \tag{3.28}$$

is the amplitude of the wave, d_1 is the distance along the positive x-axis and E_0 is a constant value of the electric field in a reference distance of 1m. The exponential term is the attenuation as a function of the traveling distance and α is the attenuation factor in [m^{-1}].

Similarly, the second wave which has a phase shift due to the reflectivity of the wall will be:

$$E_2 = E_B \sin\left(wt - kd_2\right) \tag{3.29}$$

Where

$$E_B = \frac{\Gamma Eo\exp(-\alpha d_2)}{d_2} \tag{3.30}$$

is the amplitude of the wave, d_2 is the distance along the positive x-axis and E_0 is a constant value of the electric field in a reference distance of 1m. The symbol Γ represents the reflectivity and depends on the material of the wall and the incident angle of the ray that represents the wave.

Both waves have the same frequency and speed, overlapping in space. As a result we have a disturbance which is the <u>linear superposition</u> of the two waves.

$$E_T = E_1 + E_2 \tag{3.31}$$

From trigonometric identities: sin(A+B) = (sinAcosB) + (cosAsinB).
Therefore, by the above identity and equations (3.27 and (3.29), we can write:

$$E_T=E_A[(\sin(wt)\cos(a_1)+\cos(wt)\sin(a_1)]+E_B[(\sin(wt)\cos(a_2)+\cos(wt)\sin(a_2)] \qquad (3.32)$$

By the way a is defined, it is time independent. Therefore (3.32) can be written as follows:

$$E_T=[E_A\cos(a_1) + E_B\cos(a_2)]\sin(wt) +[E_A\sin(a_1) + E_B\sin(a_2)]\cos(wt) \qquad (3.33)$$

One can observe that the bracketed quantities are constant in time. Hence let

$$E_0\cos(a)=E_A\cos(a_1) + E_B\cos(a_2) \qquad (3.34)$$

And

$$E_0\sin(a)=E_A\sin(a_1) + E_B\sin(a_2) \qquad (3.35)$$

If we square and add Equations 3.34 and 3.35, we get:

$$E_0^2=E_A^2+E_B^2+2E_AE_B\cos(a_2-a_1) \qquad (3.36)$$

Similarly, if we divide those equations, we get:

$$\tan(a)=\frac{E_A\sin(a_1)+E_B\sin(a_2)}{E_A\cos(a_1)+E_B\cos(a_2)} \qquad (3.37)$$

An expression for the total disturbance, based on Equations 3.33, 3.34 and 3.35 is:

$$E=E_0\cos(a)\sin(wt) + E_0\sin(a)\cos(wt) \qquad (3.38)$$

Which becomes

$$E=E_0\sin(wt+a) \tag{3.39}$$

We see that a single disturbance results from the superposition of the two sinusoidal waves E_1 and E_2. The composite wave shown in Equation 3.39, is harmonic and of the same frequency as the constituents. Nevertheless, its amplitude and phase are different. As discussed in the previous section, the irradiance or the flux density of a light wave is proportional to its amplitude squared (3.24). In the case of two waves, the resultant flux density is not the sum of the component flux densities. There is an additional contribution as shown from the Equation 3.36, $2E_AE_B\cos(a_2-a_1)$, known as the <u>interference term</u>.

Moreover, there is an important factor, which is the phase difference between two interfering waves

$$\delta \equiv a_2 - a_1 \tag{3.40}$$

When $\delta = 0, \pm 2\pi, \pm 4\pi, \ldots\ldots$ The resultant amplitude is maximum and the waves are in phase.

When $\delta = \pm\pi, \pm 3\pi, \ldots\ldots$ the resultant amplitude is minimum and the waves are 180° out of phase, as shown in Figure (3.5).

We saw that a phase difference may arise from a difference in path length of the two waves. It also may exist due to the difference in the initial phase angle,

$$\delta = (kx_1 + \varepsilon_1) - ((kx_2 + \varepsilon_2) \tag{3.41}$$

Which with the substitution of $k = \dfrac{2\pi}{\lambda}$, can be expressed as:

$$\delta = \frac{2\pi}{\lambda}(x_1 - x_2) + (\varepsilon_1 - \varepsilon_2) \tag{3.42}$$

Where, x_1 and x_2 are the distances from the sources of the two waves to the point of observation respectively, while λ is the wavelength.

For the purpose of this research, we assume that the waves are initially in phase, hence $\varepsilon_1 = \varepsilon_2$. In the general case where $\varepsilon_1 - \varepsilon_2 = C$ constant, the waves are said to be *coherent*. Then eqn 3.38 reduces to

$$\delta = \frac{2\pi}{\lambda}(x_1 - x_2) \tag{3.43}$$

The above equation can also be applied in the case that two waves are coming from the same source but they travel different paths before arriving at the observation point. It is also known from Equation 3.2, that the absolute index of refraction is

$$\eta = \frac{c}{u} = \frac{\lambda_0}{\lambda} \tag{3.44}$$

Then the Equation 3.43 becomes:

$$\delta = \frac{2\pi}{\lambda_0}\eta(x_1 - x_2) \tag{3.45}$$

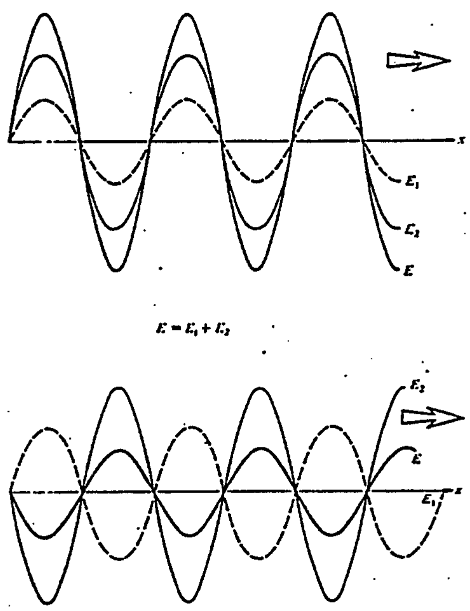

Figure 3.5: The superposition of two harmonic waves in and out of phase.

The quantity $\eta(x_1 - x_2)$ is known as the optical path difference, Λ. Since each wavelength is associated with a 2π radian phase change, by the Equation 3.39 we get that

$$\delta = k_0 \Lambda \tag{3.46}$$

Where k_0 is the wave propagation number in vacuum $\left(k_0 = \frac{2\pi}{\lambda_0}\right)$.

As we saw the irradiance is given by Equation 3.24 $I \equiv \langle S \rangle = \frac{c\varepsilon_0}{2} E_0^2$. Therefore, if we substitute the value for the field amplitude, given in Equation 3.28 in the above equation, we get a value for irradiance as a function of the two different wave amplitudes, E_A and E_B,

$$I \equiv \langle S \rangle = \frac{c\varepsilon_0}{2}\left[E_A^2 + E_B^2 + 2E_A E_B \cos(a_2 - a_1)\right] \tag{3.47}$$

Hence we can express the Irradiance as a function of the distances d_1 and d_2 that the waves have to travel from the source to the reception point, by using the expressions for E_A and E_B, from Equations 3.28, 3.30:

$$I = \left(\frac{c\varepsilon_0}{2}\right)\left[\left(\frac{E_0^2 e^{-2\alpha d_1}}{d_1^2}\right) + \left(\frac{\Gamma^2 E_0^2 e^{-2\alpha d_2}}{d_2^2}\right) + \left(2\frac{\Gamma E_0^2 e^{-\alpha(d_1+d_2)}}{d_1 d_2}\cos(a_2 - a_1)\right)\right] \tag{3.48}$$

With the above procedure we calculated the irradiance in a reception point which is at distance d from the source, and the distances or paths traveled by the two waves are d_1 and d_2. It can be shown that in case of three waves of the same frequency, the resultant amplitude would be

$$\begin{aligned} E_0^2 &= E_A^2 + E_B^2 + E_C^2 + [(2E_A E_B \cos(a_2 - a_1) + (2E_A E_C \cos(a_3 - a_1) + \\ &+ (2E_B E_C \cos(a_3 - a_1)] \end{aligned} \tag{3.49}$$

Following the same procedure, we can conclude that in general, the superposition of any number of coherent harmonic waves having the same frequency and traveling in the same direction, of the form, $E = E_i \cos(a_i \pm wt)$, is a harmonic wave of the same frequency. Hence for N such waves, the resultant amplitude is

$$E_0^2 = \sum_{i=1}^{N} E_i^2 + 2\sum_{j>1}^{N}\sum_{i=1}^{N} E_i E_j \cos(a_j - a_i) \tag{3.50}$$

And

$$\tan(a) = \frac{\sum_{i=1}^{N} E_i \sin(a_i)}{\sum_{i=1}^{N} E_i \cos(a_i)} \tag{3.51}$$

Finally the resultant wave is

$$E = E_0 \cos(a \pm wt) \tag{3.52}$$

IV. COMPUTER SIMULATION OF A TRANSMITTER AND A RECEIVER SYSTEM

In this chapter we simulate, using MATLAB 5.1, a transmitter - receiver system. Our main purpose is to investigate the role of the multipath interference in the decrease of the signal to noise ratio, compared to a transmission without interference of this type. This phenomenon affects the performance of the wireless communications systems and should be taken into consideration during the system design phase. The results of this simulation are used to evaluate the validity of a COMNET III model assumption, namely the standard data rate of 1 Mbps.

A. MODEL DESCRIPTION

The objective of this section is to calculate the irradiance generated by two interfering waves. In order to have a benchmark for comparison we first calculate the irradiance at the reception point using just the line-of-sight (LOS) ray. The calculations will be made, both with and without taking the attenuation factor into consideration.

In Figure (4.1), we see the transmitting point T and the reception point R. They are separated by a horizontal distance d. We assume that an infinite wall is at a distance h_T from the transmitter and a distance h_R from the receiver. This wall serves as the plane of reflection for the second ray. The attenuation factor is α in [m^{-1}], while the amplitude of the electric field in a distance r=1m from the source is E_0, in [V/m]. The direct separation between the two points (LOS) is d_1 and the distance for the reflected at point G ray, is d_2. The distance between the transmitter and the reflection point is d_{21}, while the distance between that point and the receiver is d_{22}.

Based on Equation 3.48, a MATLAB programming code gives the Irradiance in the reception point. This code can be found in Appendix A. Moreover, Table 4.1 shows the default parameters used for the model.

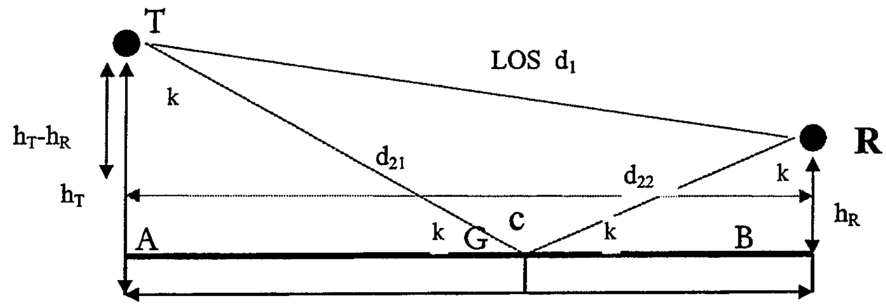

Figure 4.1 Schematic of the Transmitter - Receiver System.

In the above figure, we need to calculate the distance d_2, which is the sum of distances d_{21} and d_{22}. By applying the law of Cosines in the triangle TRG, we get:

$$d_1^2 = d_{21}^2 + d_{22}^2 - 2d_{21}d_{22}\cos(c) \tag{4.1}$$

From geometrical optics, we know that the incident angle on a surface is equal to the reflection angle (Equation 3.3 and Figure 3.2). Therefore, in our case, angle c is twice the angle k, or

$$\hat{c} = 2\hat{k} \tag{4.2}$$

from trigonometry we know that:

$$\cos(2k) = 2\cos^2(k) - 1 \tag{4.3}$$

The last useful relationship will be taken from the similarity of the triangles TAG and RBG:

$$\frac{h_T}{d_{21}} = \frac{h_R}{d_{22}} \Rightarrow d_{21} = d_{22}\frac{h_T}{h_R} \tag{4.4}$$

From the Equations 4.1, 4.3 and 4.4, we can calculate the distances d_{21} as follows

$$d_{22}^2 = \frac{\left[(h_T - h_R)^2 + d^2 + 4h_T h_R\right]}{\left(\frac{h_T}{h_R} + 1\right)^2} \tag{4.5}$$

and from Equations 4.4, 4.5 we calculate d_{21}. Finally,

$$d_2 = d_{21} + d_{22} \tag{4.6}$$

Another important parameter that we need to calculate is the Reflectivity Γ, or the amplitude reflection coefficient (r). As we have seen in the previous chapter (equations 3.5 and 3.7), in order to find reflectivity, either in horizontal or vertical polarization, we need to know the angles of incidence (θ_i) and refraction (θ_t) and the refractive indices in both media. In our case the first medium is the air, hence $n_i = 1$. After extensive search in various sources, we were unable to find realistic values of n_t for materials used for buildings, such as cement, wood, steel etc, in high frequencies (1-10 GHz). Therefore, we will use a reflectivity of 10%, as the default value, which is a good approximation for these types of materials. Nevertheless, the user can run the model for different values than the default ones. In Table 4.1 we can see the default parameters used for the model. The MATLAB programming code can be found in Appendix A.

Table 4.1 Default Parameters

Parameter	Symbol	Value
Carrier Frequency	F	2.4 GHz
Attenuation Factor	α	$0.02 \cdot 10^{-3}$ dB/m or 1m^{-1}
Wall distance for the Transmitter	Ht	10 m
Wall distance for the Receiver	Hr	2 m
Electric Field amplitude in 1 m from the source	E_o	1 V

Reflectivity 10%	Γ	0.1
Horizontal distance	D	From 2 m to 500 m
Plotting data pairs		3000
Permittivity	ε_o	$8.8542 \cdot 10^{-12}$ C^2/Nm^2

B. IRRADIANCE WITH NO ATTENUATION

In the following Figures (4.2 and 4.3), we can see the Electric Field magnitude in [V/m] and the Irradiance in [W/m^2] as functions of the horizontal distance d in [m]. First we assume that only one wave is transmitted from T and travels to the reception point R in a straight path, or in the Line Of Sight (LOS). The attenuation factor α has not been taken into consideration.

In Figure 4.2, the amplitude of the electric field decreases with the distance and eventually goes to zero. Since the vertical axis represents the magnitude of the field, both positive and negative values are plotted. In Figure 4.3, the irradiance has its maximum value at the source and also decreases with the distance. Since only one wave is transmitted, there is no interference at the reception point.

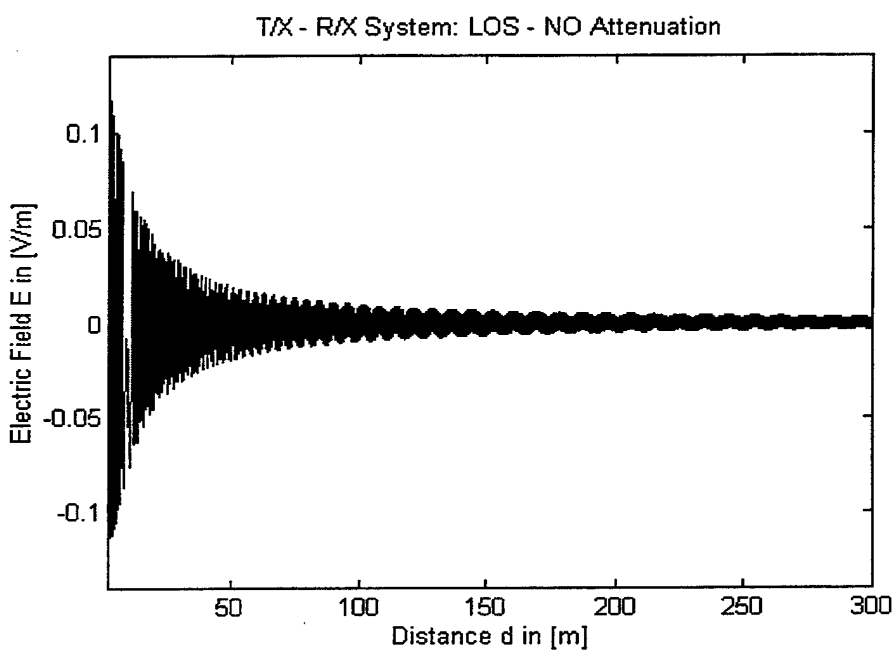

Figure 4.2 Electric field vs Distance

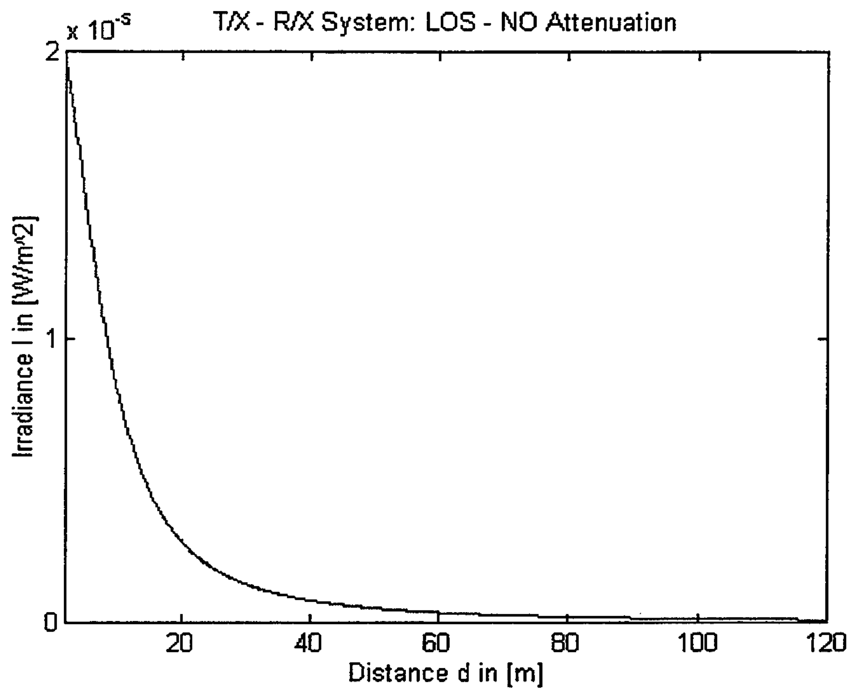

Figure 4.3 Irradiance vs Distance

Now, a second wave is transmitted from the source, travels the distance d_{21} shown in Figure 4.1 and hits the infinite wall of reflectivity Γ. After picking up a phase difference (due to the reflection), it travels the distance d_{22} towards the reception point. Meanwhile, the first wave travels in a straight line a smaller distance d_1. In this case there is interference at the reception point due to the path difference of the two waves. In Figures 4.4 and 4.5 we see the electric field and the Irradiance as functions of the horizontal distance, respectively. Note that in Figure 4.4, the amplitude of the field is plotted, therefore there are only positive values.

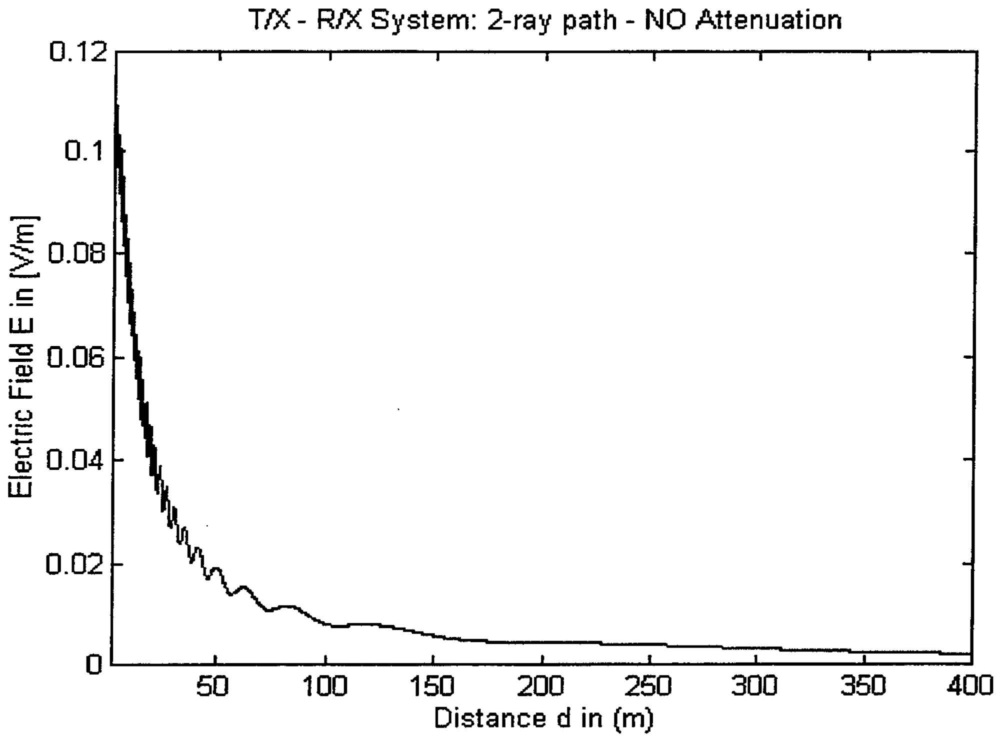

Figure 4.4 Electric Field vs Distance

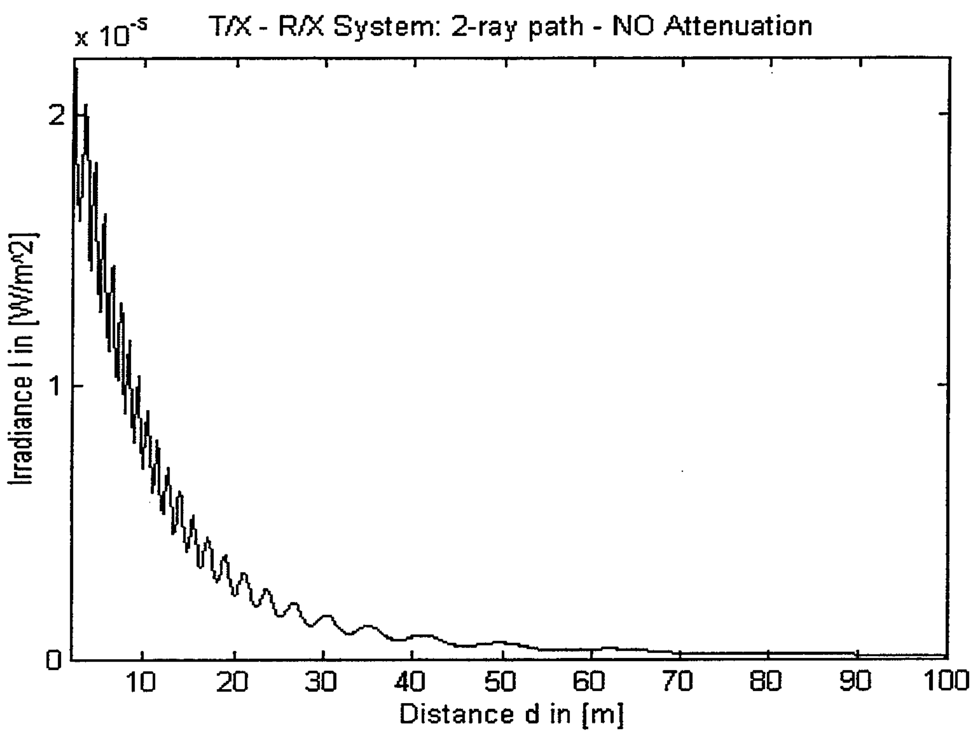

Figure 4.5 Irradiance vs Distance

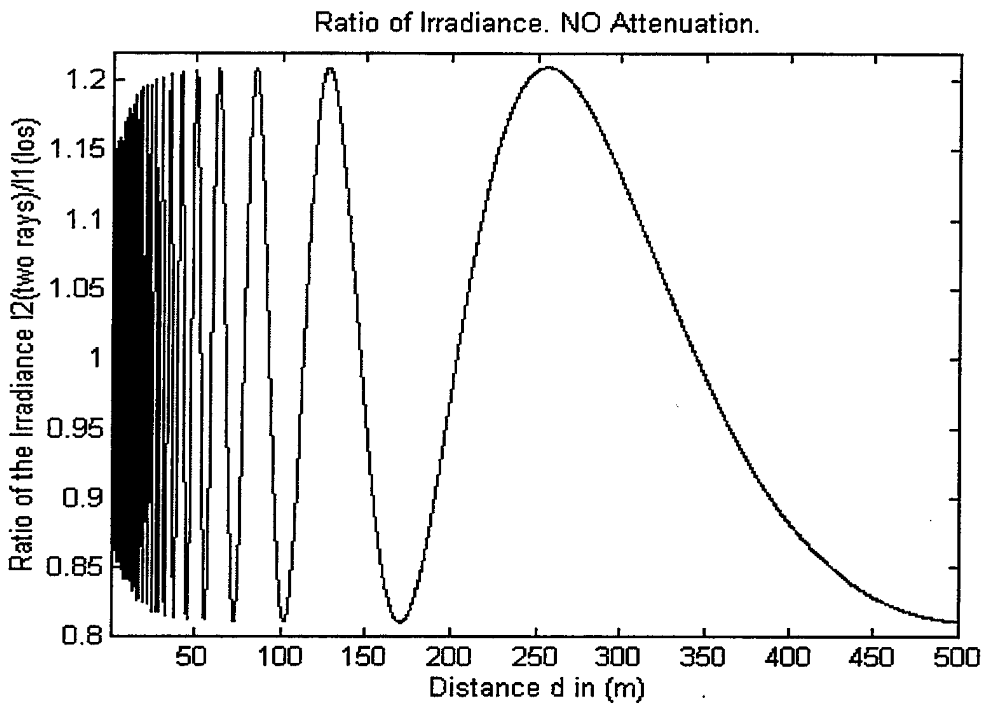

Figure 4.6 Ratio of Irradiances vs Distance

Finally, the ratio of the Irradiances presented in Figures 4.3 and 4.5 is shown in Figure 4.6. This figure shows the relative variation in the received signal due to multipath interference. We see that the fluctuation of this ratio is from 0.81 to 1.21. Since in general one can't control the separation distance or the location of the reflecting surface, one should expect a variation of ± 20%. This fact leads to the conclusion that a worst case signal-to-noise ratio is approximately ± 20%. Thus we have that

$$\frac{S}{N} = \frac{1}{0.2} = 5 \tag{4.7}$$

We also know that the channel capacity is given by the Shannon formula

$$C = W \log_2 (1 + \frac{S}{N}) \tag{4.8}$$

Where, C denotes the capacity in bits per second (bps), W the bandwidth in Hertz.
Knowing either the channel capacity for a given link or the bandwidth limitations we can design a communication system.

The wireless local area network protocol that we need to simulate, supports the Frequency Hopping Spread Spectrum modulation technique, as described at section D of Chapter V. Given that for this scheme the bandwidth proposed is 1 MHZ, from Equation 4.8 we get that the channel's higher data rate C, is 2.6 Mbps.

Now, given that the IEEE's standard proposes either 1 or 2 Mbps data rate, we assume that the COMNET III assumption of 1Mbps is valid. Therefore, we use 1Mbps for the link's data rate and the propagation delay for a distance of 100 meters, where the signal is non significantly attenuated, is 0.05 microseconds. These numerical values are used for the development and simulation of the wireless local area network in Chapter VII.

Finally, we need to mention that for the used frequency of 2.4 GHz, the attenuation factor is negligible. Therefore, the results of the simulation will not change if we take this factor into account. Nevertheless, in Appendix A we present the programming code for both cases, with and without the attenuation factor, since we know that for different frequencies this factor has to be included in the calculations.

V. WIRELESS NETWORKS

In this chapter we introduce the Wireless Networks. After a brief historical review, we talk about their advantages and design considerations, the utilization of Spread Spectrum modulation techniques and the existing protocols in Wireless Networks.

A. HISTORY OF WIRELESS NETWORKS

The first attempt to merge network technologies and radio communication began in 1971 at the University of Hawaii as a research project called ALOHANET. The ALOHANET system enabled computer sites at seven campus spread out over four islands to communicate with the central computer on Oahu without using existing, unreliable, expensive phone lines. The system offered bi-directional communications, in a star topology, between the central computer and each of the remote stations. The remote stations had to communicate with each other via the centralized computer.

After ALOHANET became popular, the U.S. military embraced the technology, and DARPA (Defense Advanced Research Projects Agency) began testing wireless networking to support tactical communications in the battlefield. Because of' limited spectrum allocations, radio-based networks could only deliver very low data rates. The researches conducted both by University of Hawaii and DARPA led to the development of the initial Ethernet technology, and the radio-based networks available today.

In 1985, the Federal Communications Commission (FCC) made the commercial development of radio-based LAN components possible by authorizing the public use of the Industrial, Scientific and Medical (ISM) bands, in the frequencies of 2.400 – 2.484 GHz (see Ch II). The ISM band is very attractive to wireless network vendors because it provides a part of the spectrum upon which to base their products, and end users do not have to obtain FCC licenses to operate the products.

During the late 1980s, the constantly decreasing size of computers from desktop machines to laptops encouraged the development of mobile computing. Computer companies focused on developing products that would support wireless connectivity methods. In 1990, NCR began shipping WaveLAN, one of the first wireless LAN adapters for PCs. Motorola

was also one of the initial wireless LAN vendors with a product called Altair. These early wireless network adapters had limited network drivers, but soon worked with almost any network operating system. The wireless technology, however, was not widely embraced due to the extremely high cost of the products. Furthermore, security and standardization problems, along with the smaller, compared to Ethernet data rate, kept network managers and system administrators from switching to wireless networks.

The depressed state of the wireless LAN market improved as standards matured. The Institute for Electrical and Electronic Engineers (IEEE) 802 Working Group, responsible for the development of LAN standards such as ethernet and token ring, initiated the 802.11 Working Group which developed a standard for wireless LANs, named CSMA/CA, in 1997. This protocol will be analyzed later on this chapter.

The following Figures 5.1 and 5.2 show the physical components of a wireless network and its logical architecture respectively.

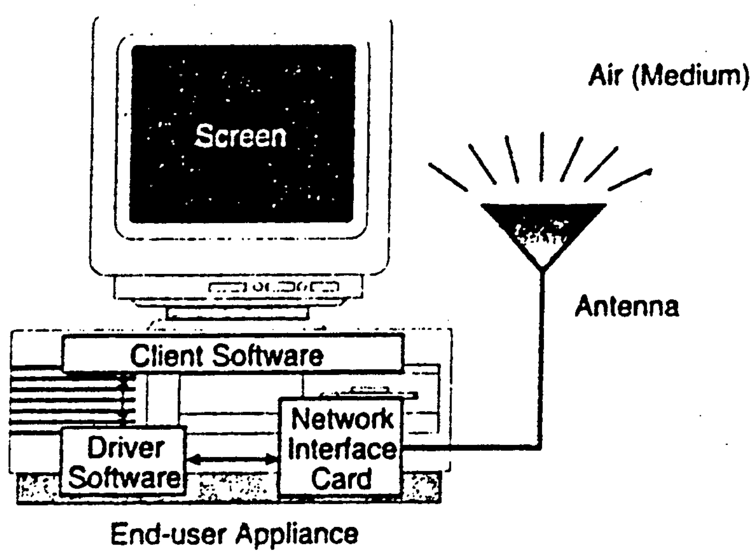

Figure 5.1 The physical components of a wireless network

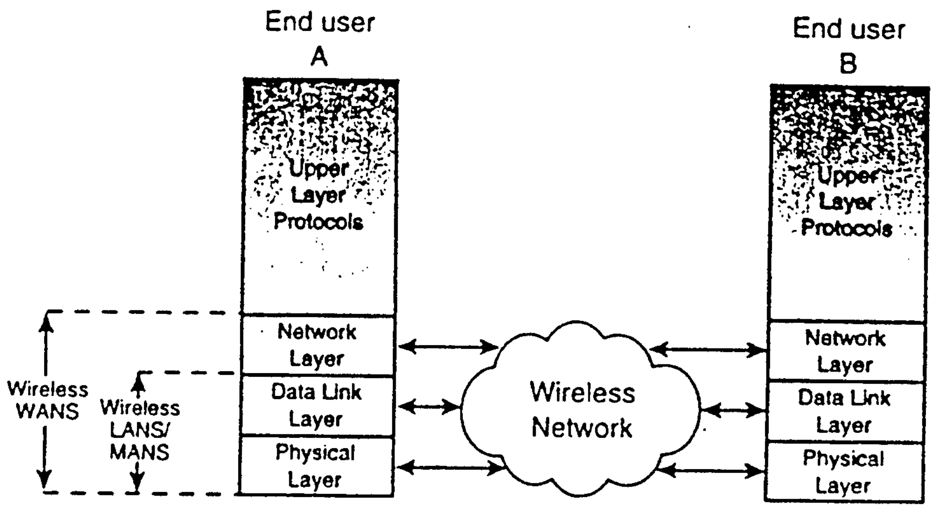

Figure 5.2 The wireless network logical architecture

B. ADVANTAGES AND DESIGN CONSIDERATIONS

The wireless networks have certain advantages over the wired ones. The most important are the following:

1. User Mobility

It indicates constant physical movement of the person and his network appliance. A good example is the wireless cellular phone, with which one can walk freely within one's office, home, or even talk to someone while driving a car. Wireless networking offers mobility to its users much like the wireless phone, providing a constant connection to information on the network. The main idea is that one cannot become mobile unless one eliminates the wire through the use of wireless networking.

2. Ease of installation in difficult-to-wire areas

The implementation of wireless networks offers many tangible cost savings when performing installations in difficult-to-wire areas. Wireless networking offers a reliable alternative to some organizations that spend millions of dollars to install physical links with nearby facilities. In addition, in some cases, it might be impossible to install cabling. A good

example is the restriction that authorities may apply to the modification of old buildings with historical value, or a limited budget.

3. Reduced installation time

The installation of cabling is often a time-consuming activity. For LANs, installers must pull twisted-pair wires above the ceiling and drop cables through walls to network outlets that they must affix to the wall. These tasks can be extremely time consuming. In the case of optical fiber, even the installation to nearby buildings requires time, since it consists of digging trenches to lay the fiber or pulling the fiber through an existing conduit. Therefore, if there is no existing network infrastructure, the wireless networking is the only method that provides connectivity among computers without the expense and time associated with installing physical media.

4. Increased reliability

Another problem inherent to wired networks is the downtime due to cable faults. Moisture erodes metallic conductors. These imperfect cable splices can cause signal reflections that result in unexplainable errors. Furthermore, the accidental cutting of cables can also bring a network down quickly. Sometimes, water intrusion can also damage communications lines during storms and floods. The advantage of wireless networking, then, is experiencing fewer problems because less cable is used.

5. Long-term cost savings

Changes and renovations in the working environment often lead to re-cabling the network, incurring both labor and material costs. In some cases, the re-cabling costs of organizational changes are substantial, especially with large enterprise networks. The advantage of wireless networking is again based on the lack of cable, since one can move the network connection by simply relocating an employee's PC.

On the other hand, one could easily see that there are some major concerns, which surround the design, implementation and use of a wireless network. Some of those are:

1. Radio signal interference

The purpose of radio-based networks is to transmit and receive signals efficiently over airwaves. This process makes these systems vulnerable to ambient noise and transmissions from other systems. In addition, these wireless networks could interfere with other radio wave equipment. This kind of interference may be inward or outward.

a. Inward Interference

An example of inward interference is the static caused on a wireless phone from a remote control of a garage door. This type of interference might also disturb radio based wireless networks. A radio-based LAN can experience some inward interference either from the harmonics of transmitting systems or other products using ISM-band frequencies in the local area. The most typical example is the problem caused by a microwave oven that operates in the S band (2.4 GHZ), since this is a frequency that many wireless LANs transmit and receive. These signals result in delays to the user by either blocking transmissions from stations on the LAN or causing bit errors to occur in data being sent. As a result, the area in which you can deploy a wireless network is limited.

In addition to the above, most radio-based products operate within the public, license free, ISM bands. These products do not require users to obtain FCC licenses, which means the FCC does not manage the use of the products. Furthermore the Committee will not resolve any type of conflict caused by such interference, leaving the victim with the choice of dealing with delays caused by that and looking for different technology solutions.

Interference with radio based networks is not as bad as it might seem. The products in the ISM bands use spread spectrum modulation. This technique limits the amount of damage that an interfering signal can cause. The spread spectrum signal covers a wide amount of bandwidth, and typical narrow bandwidth interference only affects a small part of the information signal, resulting in few or no errors, as will be seen later in this chapter. Thus, spread spectrum-type products are highly resistant to interference.

b. Outward Interference

It occurs when a wireless network's signal disrupts other systems, such as adjacent wireless LANs, navigation equipment on aircraft, etc. This disruption results in the loss of some or all of the system's functionality. Interference is uncommon with ISM band products because they operate little power. Only when the transmitting components are very close and operate in the same bandwidth one can experience inward or outward interference.

2. Power management

The mobile computing depends on the battery duration of the device, since it is not always easy to find an electrical outlet in the area that you need to operate it (eg in a car). The extra load of the wireless Network Interface Card (NIC) in this situation can significantly decrease the amount of time you have available to operate the computer before needing to recharge the batteries. The operating time, therefore, might decrease to less than an hour if you access the network often. This very important issue lead the industry to the implementation of several different management techniques, in order to conserve power.

3. System interoperability

The existence of a stable standard (eg IEEE 802.3 for Ethernet), in the wired networks allows the deployment of NICs[4] from various vendors. This standard specifies the protocols and electrical characteristics that manufacturers must follow for Ethernet, in order for the products to speak exactly the same language. Today, this is not possible with most wireless network products, especially wireless LANs and MANs. The selection of these wireless products is predominantly single vendor, sole-source acquisitions. Products from one vendor will not inter-operate with those from a different one. As mentioned earlier, the solution to this problem, at least for wireless LANs, is the new standard created by IEEE 802.11 Working Group.

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[4] NIC: Network Interface Card

4. Network security

Network security refers to the protection of information and resources from loss, corruption, and improper use. The main security issue with the wireless networks is that they intentionally propagate data over an area that may exceed the physically controlled limits. For example, radio waves easily penetrate building walls and are receivable in a certain distance. Someone can passively retrieve any sensitive information by using the same wireless NIC from this distance, without being noticed by the security personnel. Figure 5.3 illustrates this concept.

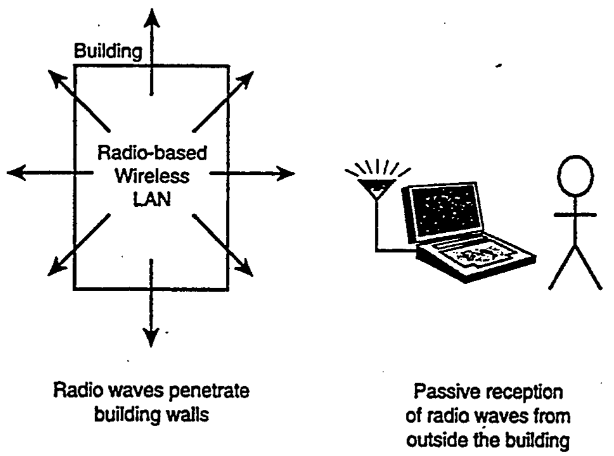

Figure 5.3 Passive reception of a wireless network data

Another security threat is the potential for electronic sabotage, in which someone maliciously jams the radio-based network. As we see later on this chapter, wireless networks utilize a carrier sense protocol to share the use of the common medium. If one station is transmitting, the others have to wait. Thus, someone can jam the network by setting up a station to continually send packets. These transmissions block all stations in that area.

The solution to most security problems, is the restriction of data access. Therefore, most networks require an access code. Another way to address security problems is data encryption in conjunction with the spread spectrum transmission techniques. There are many encryption algorithms, used in the wireless LANs. A popular one is according to the Data Encryption Standard (DES) as defined by the U.S. Department of Commerce, National

Institute of Standards and Technology (NIST), formerly called the National Bureau of Standards (NBS). Another similar algorithm is the Advanced Encryption Scheme (AES).

The DES and AES algorithms use a 16-digit hexadecimal key for encryption. The key is loaded into the security chip when the adapter is configured at installation. When a message is received or sent, the security chip uses the key to encrypt or decrypt the message. Only those workstations in the network with the same security chip and key will be able to understand the messages. Other users who do not have the key will be unable to decrypt any messages. Both DES and AES perform the encryption in one continuous stream of bits that pass through the system's modulator without affecting performance.

Figure 5.4 shows a graphical representation of the data encryption process.

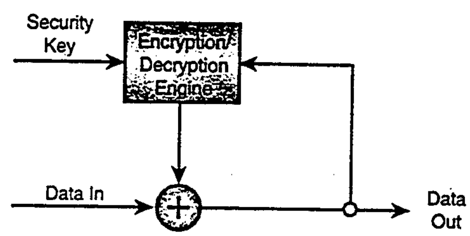

Figure 5.4 The data encryption process

5. Installation issues

With wired networks, planning the installation of cabling is fairly straightforward, while implementation is labor intensive and often difficult. A radio-based wireless LAN installation is not as predictable. It is difficult, if not impossible, to design the wireless system by only inspecting the facility. Predicting the way in which the contour of the building will affect the propagation of radio waves is difficult. Omni-directional antennas propagate radio waves in all directions if nothing gets in the way. Walls, ceilings, and other obstacles attenuate the signals more in one direction than the other, and even cause some waves to change their paths of transmission. These events cause the actual radiation pattern to distort, taking on a jagged appearance. To avoid installation problems one should perform propagation tests to assess the

coverage of the network. Neglecting to do so may leave some of the users outside of the propagation area of wireless servers and bridges.

6. Health risks

Another common concern is whether wireless networks pose any form of health risk. So far, there has been no conclusive answer. Wireless network components should be even safer than cellular phones because they operate at lower power levels, typically between 50 and 100 milliwatts. In addition, wireless network components usually transmit for shorter periods of time. Furthermore, laser-based products, found in both wireless LANs and MANs, offer very little or no health risks.

C. WIRELESS LAN TRANSMISSION TECHNIQUES

The first wireless networks used narrowband FM radio. Narrowband radio had the advantages of simple design, low cost, good range, and legal protection against interference through end-user licensing. Narrowband FM radios are still in use for expanding older networks.

Nowadays, spread-spectrum is the dominant technology for wireless LANs. Spread-spectrum radio may be employed without obtaining an operator's license, a fact that customer readily appreciates. Unlicensed operation means users can freely transfer devices from one location to another. Although spread-spectrum signals consume considerably more bandwidth than narrowband FM signals, there is much more bandwidth available to spread-spectrum radios, so they manage to run at much higher speeds. While most narrowband FM transceivers communicate at 9,600 bps, spread-spectrum transceivers are usually rated at speeds ranging from 100 Kbps to 2 Mbps.

The reason the FCC agreed to permit spread-spectrum radios to be operated without end-user licenses is that the technology is relatively immune to interference both inward and outward. Spread-spectrum signals occupy a much wider frequency range than the conventional ones. As a result, spread-spectrum signals are nearly invisible to narrowband radios, and vice versa. This fact does not exclude the possibility of interference, but it decreases it significantly.

In any event, it is the spread-spectrum end-user that takes on the risk, as the FCC does not generally protect unlicensed users.

The two major spread-spectrum techniques are the Direct Sequence Spread Spectrum and the Frequency Hoping Spread Spectrum.

1. Direct Sequence Spread Spectrum (DSSS)

This technique works by expanding the signal over a continuous wide band channel. This is accomplished by combining the data signal with a much higher bit rate pseudo random signal[5]. In essence, the information is "buried" within what looks like white noise.

Another way to look at DSSS is that each single bit of data is represented by a string of special bits called "chips." While we attach great importance to each bit of ordinary binary data the spread-spectrum chip stream is highly redundant. A simple example is presented in Figure 5.5). We assume that a sequence of 7-chip spreading code (1010111) is used to hide the user data sequence of five bits (11001). Now, we assume that both real data and spreading bit sequence are passed through an "exclusive or" (XOR) gate to create the transmitted chirp stream. This stream looks like a noise[6] to a receiver that does not have the spreading code. On the other end, the friendly receiver knows the spreading code and passes the received sequence from a new XOR gate to reproduce the original data. The receiver only needs to receive four of the spreading chips correctly to determine the correct data bit. That is, the identity of the information bit may be determined by a "best of seven" accounting.

Both major types of spread-spectrum share a number of benefits. Given the fact that the signals occupy a wide channel, they are strongly resistant to multipath interference, which is a frequency-specified impairment, as we saw in Chapters III and IV. Spread-spectrum systems can communicate successfully even in the presence of relatively strong narrowband interference. This fact makes spread-spectrum practically immune to jamming. Moreover, the spreading process improves the communication's security as only those possessing the correct spreading code can decode the signals.

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[5] A pseudo-noise or pseudo-random sequence is a binary sequence with an autocorrelation that resembles, over a period, the autocorrelation of a random binary sequence. It also roughly resembles the autocorrelation of a white noise. [ref 13, p.275].

[6] A feedback shift register is used to create an output that resembles the noise. [ref 13, p.276].

DSSS has the specific advantage of being relatively inexpensive to implement. It is also possible for multiple DSSS users to communicate over the same wideband channel at the same rime. This is the basis for the code division multiple access (CDMA) technology used in cellular and PCS networks. However, most DSSS wireless LANs do not use CDMA. Nevertheless, a few do use code division as a means of isolating nearby cells from each other, since a DSSS signal employing a different code looks like white noise to a another receiver, as does a narrowband signal.

The disadvantage of DSSS relative to frequency hopping technique is that it is more vulnerable to narrowband interferers. That is, while a single, strong interferer may only slow down a frequency hopping LAN, a direct sequence LAN may be totally disrupted by such a signal. The DSSS receiver is listening over the entire wideband channel all of the time, so there is normally no escaping strong interference within that channel. This is the main reason why the majority of wireless LANs uses frequency hoping.

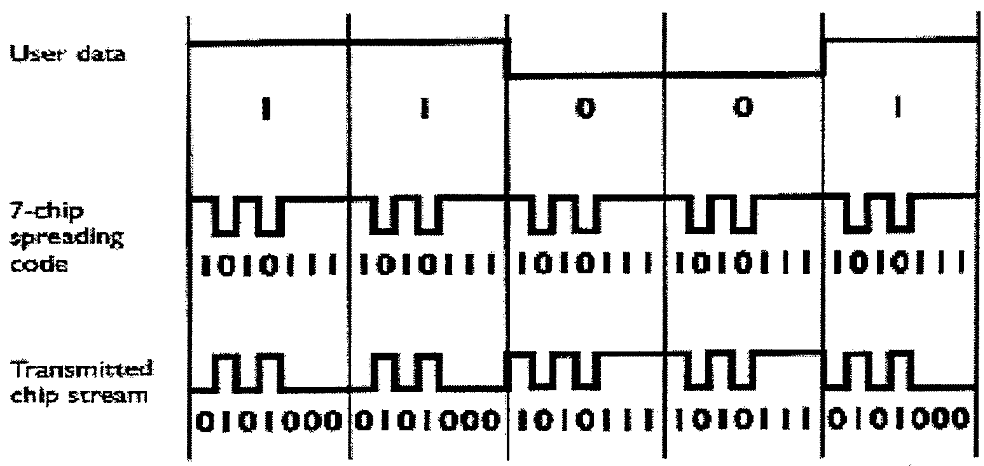

Figure 5.5 Direct Sequence "chirp" concept

2. Frequency Hopping Spread Spectrum (FHSS)

A frequency hopper uses a narrowband signal that rapidly and continuously changes frequency. Like DSSS, frequency hopping spread spectrum (FHSS) involves combining an

information signal with a pseudo random signal. The pseudo random signal may be used to control the hopping sequence, the transmitted bit sequence, or both.

There are different types of FHSS systems. In fast FHSS, the transmitter sends just one chip per hop. Thus, several hops are required to convey a single bit. In fact direct sequence could be described as simply very fast frequency hopping. In slow FHSS, multiple bits are sent per hop, hence there are no chips. In other words, the slow hopper is a conventional signal that simply changes frequency, as seen in Figure 5.6. There is no strict separation between fast and slow hoppers. Practically, a hopper is considered fast when it makes more than 100 hops per second. Someone may also claim that slow frequency hopping is not really spread-spectrum as the data is combined with a lower rather than higher bit rate signal. Another classification of frequency hoppers is the coordinated versus the asynchronous. Coordinated hoppers permit multiple simultaneous sessions between a hub and a number of associated remote stations. This ensures that the remote stations do not step on each other's data. In essence, coordinated hoppers share the same pseudo random sequence. Asynchronous hoppers are used in multi-hub systems; they share the same channels on an uncoordinated basis, with occasional data collisions. Asynchronous hopping permits unrelated users to share the same spectrum.

The big advantage of FHSS is that it can better coexist with narrowband interference. While the DSSS receiver must listen over the entire wideband channel all of the time and is susceptible to a strong interferer anywhere within that channel the FHSS receiver only listens on its current narrowband channel. If it hops to a channel where it encounters strong interference, communications may be interrupted. So, while a DSSS communications link may be shut down by a sufficiently strong interferer the FHSS link will be merely interrupted. The FHSS transmitter can simply buffer the data and re-send it once it hops (as scheduled) to another frequency. The CDMA cellular and PCS networks need not to worry about this problem, as they are protected users within their frequency allocations. A typical band example, for military applications, is 225 - 400 MHz. Using a 25 KHz inter-channel separation, this type of system can utilize 7,000 different channels for hopping.

The drawbacks to FHSS are: 1) fast FHSS is expensive to implement, and 2) slow FHSS is more vulnerable to multipath interference as well as other impairments that typically affect narrowband systems.

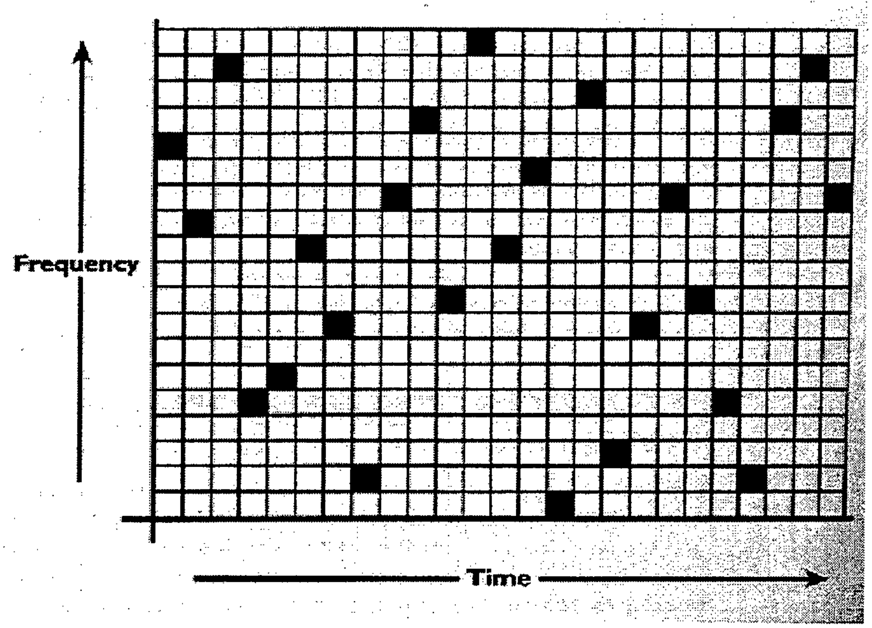

Figure 5.6 Frequency Hopping diagram

D. WIRELESS LAN PROTOCOLS

As previously discussed, one of the major problems of the wireless LAN development was the lack of standardization. Since the wireless LANs have different properties than the conventional ones, they required special medium access control (MAC) layer protocols.

1. Carrier Sense Multiple Access with Collision Detection (CSMA/CD)

The first attempt to apply a MAC protocol to a wireless LAN was with the CSMA/CD. According to that, a station has to listen to other transmissions and only transmit if no one else is doing so. Unfortunately, this protocol was not the best solution since what matters is interference at receiver and not at the sender. To demonstrate the problem, we see in Figures 5.7 and 5.8 a wireless LAN of four stations, A, B, C and D. The distance is such that

A and B are within each other's radio range and can potentially interfere with one another. C can also interfere with both B and D, but not with A.

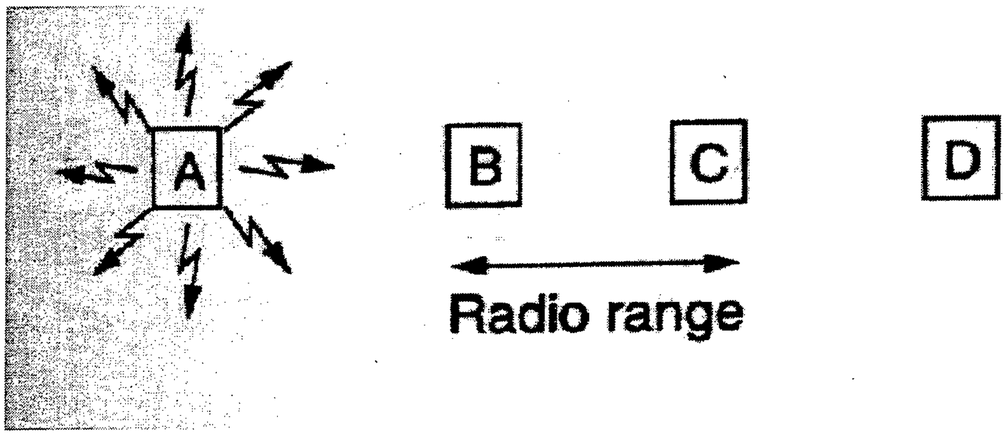

Figure 5.7 Four stations wireless LAN: Station A is transmitting

When A transmits to B, as shown in Figure 5.7, C senses the medium and is not able to hear A, since it is out of range. Thus, it falsely concludes that it can transmit. When C starts transmitting it interferes with A at B. The problem of a station not being able to detect a potential competitor for the medium due to the distance between them, is called the <u>hidden station problem.</u>

On the other hand, we assume that B transmits to A, as shown in Figure 5.8. Station C senses the medium, hears the ongoing transmission and falsely conclude that it cannot send to D. In fact, such a transmission would cause reception problems only in the zone between B and C, where neither of the intended receivers is located. This situation is called the <u>exposed station problem.</u>

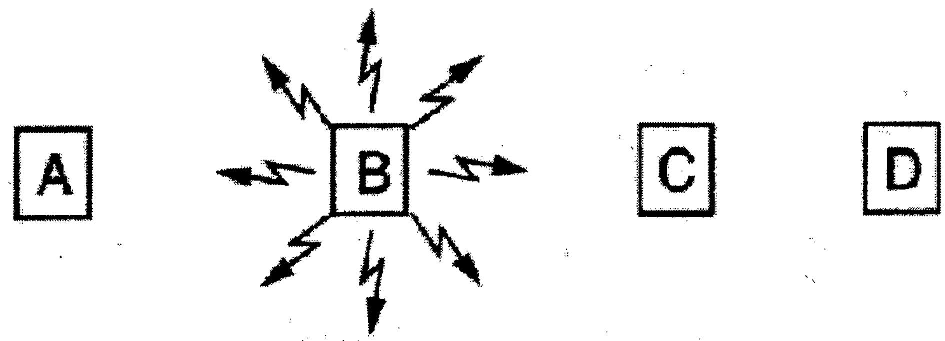

Figure 5.8 Four stations wireless LAN: Station B is transmitting

As we saw, it is essential for a station to know if there is activity around the intended receiver. In a system based on radio waves, multiple transmissions can occur simultaneously, if they all have different destinations that are out of one another's range.

2. Multiple Access with Collision Avoidance (MACA)

An early protocol for wireless LANs is MACA (Karn, 1990). It was used as the basis for the IEEE 802.11 wireless LAN standard. The basic idea behind it is for the sender to stimulate the receiver into outputting a short frame. This way, stations nearby can detect this transmission and avoid transmitting for the duration of the following data frames. In Figures 5.9 and 5.10 we see a LAN that consists of five stations.

Station A intends to transmit a data frame to station B. It starts by sending a short RTS (Request To Send) frame, as shown in Figure 5.9. This short frame (30 bytes), contains the length of the data frame that will eventually follow. Station B replies with a CTS (Clear To Send) frame, as shown in Figure 5.10. The CTS frame also contains the data frame length, copied from the RTS one. Upon receipt of the CTS frame, station A begins transmission.

Now let us see how stations overhearing either of these frames react. Any station hearing the RTS is inside A's radio range and it must remain silent long enough for the CTS to be transmitted back to A without conflict. Any station hearing the CTS is closer to B and has to remain silent during the upcoming data frame, whose length is known to it.

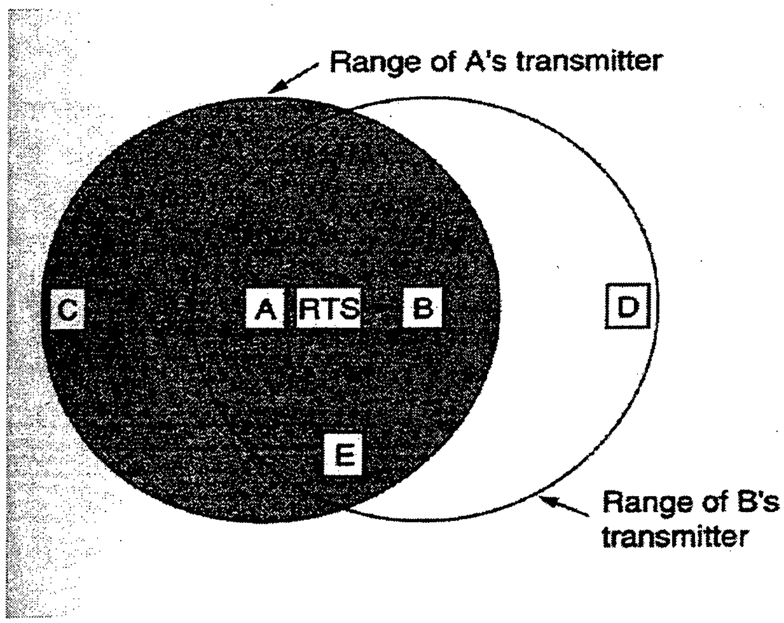

Figure 5.9 The MACA protocol: A sends RTS to B

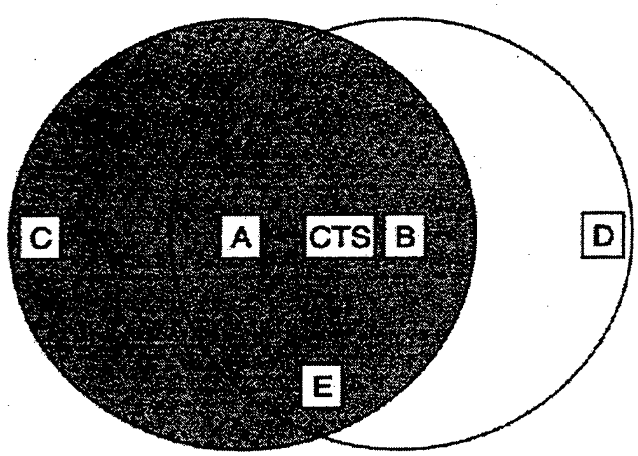

Figure 5.10 The MACA protocol: B sends CTS to A

In Figure 5.9, we see that station C is within range of A but not within range of B. Thus, it only hears the RTS from A. As long as it does not interfere with the CTS, it is free to transmit while the data frame is being sent. On the other hand, station D is within range of B but not A. Thus it hears only the CTS frame. To that station it means that a nearby station is about to receive a data frame, so it defers from sending anything until the transmission is expected to be finished. Station E hears both messages, and like D, stays silent until the data frame is complete.

Despite these precautions, collisions can still occur. In the event of a collision, an unsuccessful transmitter (one that does not hear a CTS within the expected time interval) waits a random amount of time and tries later. The algorithm used is binary exponential backoff.

3. MACAW

Based on simulation studies of MACA, Bharghavan (1994) fine tuned MACA to improve its performance and renamed the new protocol MACAW. The simulation showed that without data link layer acknowledgements, lost frames were not retransmitted until the transport layer noticed their absence, much later. Introducing an ACK (acknowledgement) frame after each successful frame solves this problem. Furthermore, carrier sensing is used to keep a station from transmitting an RTS at the same time another nearby station is also doing so to the same destination. In addition, the backoff algorithm runs separately for each data stream (source-destination pair), rather than for each station. This change improves the fairness of the protocol. Finally, there is a mechanism for stations to exchange information about congestion, and a way to make the backoff algorithm react less to temporary problems.

4. CSMA/CA Wireless LAN IEEE 802.11

IEEE 802.11 is the standard for Wireless Local Area Networks (WLANs) developed by the Institute of Electrical and Electronics Engineers (IEEE). It can be compared to the 802.3 standard for ethernet wired LANs. The goal of this standard is to tailor a model of operation in order to resolve compatibility issues between manufacturers of WLAN equipment manufacturers.

The Medium Access Control (MAC) under 802.11 is composed of several functional blocks. These include mechanisms to provide contention and contention-free access control on a variety of physical layers. The functions within the MAC are independent of data rates or physical characteristics. The fundamental access method of the 802.11 MAC is known as Carrier Sense Multiple Access with collision avoidance or CSMA/CA. It works by a "listen before talk scheme."

Each station wishing to transmit first senses the medium to determine if another station is transmitting. If the medium is not busy, the transmission may proceed. The IEEE 8O2.11 distributed algorithm mandates that a gap of a minimum specified duration (called the Distributed Inter-Frame Space, or DIFS) exists between contiguous frame transmissions. A transmitting station ensures that the medium is idle for this DIFS duration before attempting to transmit. If the medium is sensed busy, the station defers until the end or the current transmission. After deferral, or prior to attempting to transmit again immediately after a successful transmission, the station selects a random backoff interval and decrements the backoff interval counter while the medium is free. When the backoff interval counter reaches zero, the station proceeds to transmit the data. The CSMA/CA protocol is designed to reduce rather than eliminate the collision probability between multiple stations accessing a medium at the point where collisions would most likely occur. Just after the medium becomes free following a busy period is when the highest probability of a collision occurs. Therefore a random backoff arrangement is immediately applied in this situation. In addition, all directed (non-multicast) traffic uses immediate positive acknowledgments (ACK frames). The sender schedules retransmission if no ACK is received. This scheme allows automatic medium sharing between several devices. This access method is attractive because it provides spectral efficiency as well as asynchronous data transfer.

The physical layer under 802.11 includes diffused infrared (DFIR), direct sequence spread spectrum (DSSS), and frequency hopped spread spectrum (FHSS). Both spread spectrum techniques are used in the 2.4 GHz band because of wide availability in many countries and lower hardware costs in comparison to the higher microwave frequencies.

The IEEE standard supports DSSS for use with BPSK[7] modulation at a 1 Mbps data rate, or QPSK[8] modulation at a 2 Mbps data rate. The general band plan consists of five overlapping 26 MHz sub-bands centered at 2.412, 2.427, 2.442, 2.457, and 2.470 GHz. This scheme is used in an attempt to combat interference and selective fading.

FHSS is supported under 802.11 with FSK[9] modulation and two hopping patterns with data rates of 1 Mbps and 2 Mbps. Under this scheme, the band is divided into 79 sub-bands with 1 MHz bandwidth each. Each sub-band is subject to a minimum rate of 2.5 hops per second using any of three possible hop patterns (22 hops in a given pattern). The minimum hop rate ensures that each packet sent could be transmitted in a single hop so that destroyed information could be recovered in another hop. This allows an effective frequency diversity that provides excellent transmission characteristics.

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[7] Binary Phase Shift Keying [ref 16, p. 1169, 1187-1189].

[8] Quadri Phase Shift Keying [ref 16, p. 667-678, 685-688].

[9] Frequency Shift Keying [ref 16, p. 21, 32-35].

VI. COMNET III DESCRIPTION

COMNET III is a graphical software package, which is capable of analyzing and predicting the performance of networks ranging from simple LANs to complex enterprise-wide systems, quickly and easily. It supports a building-block approach where the blocks are "objects" that the user is familiar with in the real world. There is a library that closely model the objects in real networks, with one COMNET III object representing one or more real world objects. Their parameters are easily adjusted to match the real ones.

Since the simulation is object-oriented, the user has the flexibility to try an unlimited number of different scenarios. User's recommendations will be supported by an easy to understand animated picture of the selected network configuration. Furthermore, no programming is required.

A. SOFTWARE DESCRIPTION

COMNET III is a performance analysis tool for computer and communication networks. Based on the description of a network, its control algorithms and workload, it simulates the operation of the network and provides measures of its performance. Network descriptions are created graphically through an intuitive interface that speeds model formulation and experimentation.

The program is integrated into a single windowed package, shown at Figure 6.1, which performs all functions of model design, execution and presentation of results.
A model is built and executed in the following steps:

(1) Nodes, links and traffic sources are selected from a palette and dragged into position on the screen. Moreover, there is an option to automatically import the topology from Network Management Systems such as OpenView, NetView, and Spectrum.

(2) These elements are connected (using the connection tool) to define their interrelationships.

(3) The user double clicks on nodes, links or traffic sources. A dialog box with all adjustable parameters appears and the user specifies the parameters, for this particular item.

(4) Network operation and protocol parameters are set on additional dialog boxes accessed through the menubar

(5) The model is verified and executed and finally the results are presented in various reports.

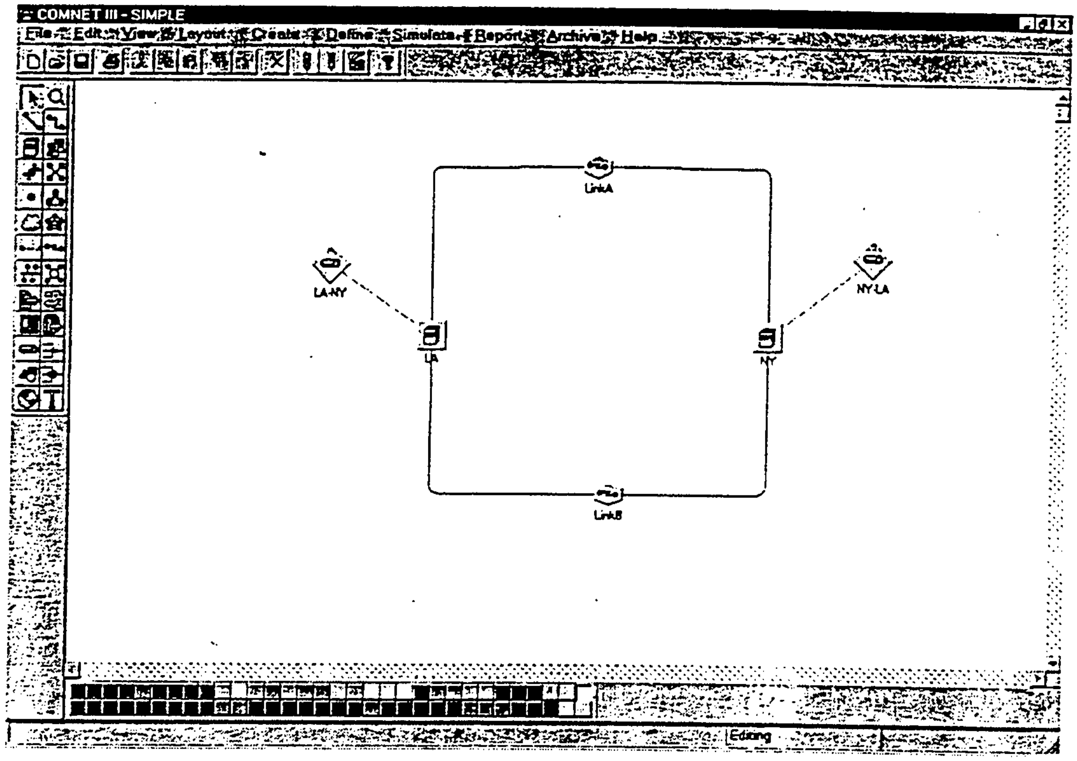


Figure 6.1 COMNET III User Interface

B. CAPABILITIES

COMNET III can be used to model both Wide Area Networks (WANs) and Local Area Networks (LANs). Moreover, its models may contain both types of networks in one integrated model. It also provides detailed modeling of network node logic. A node's computers, their I/O subsystems, their databases and the applications that run on the computers can be modeled.

The network modeling approach used in COMNET III is designed to accommodate a wide variety of network topologies and routing algorithms, like the one shown on Figure 6.2.

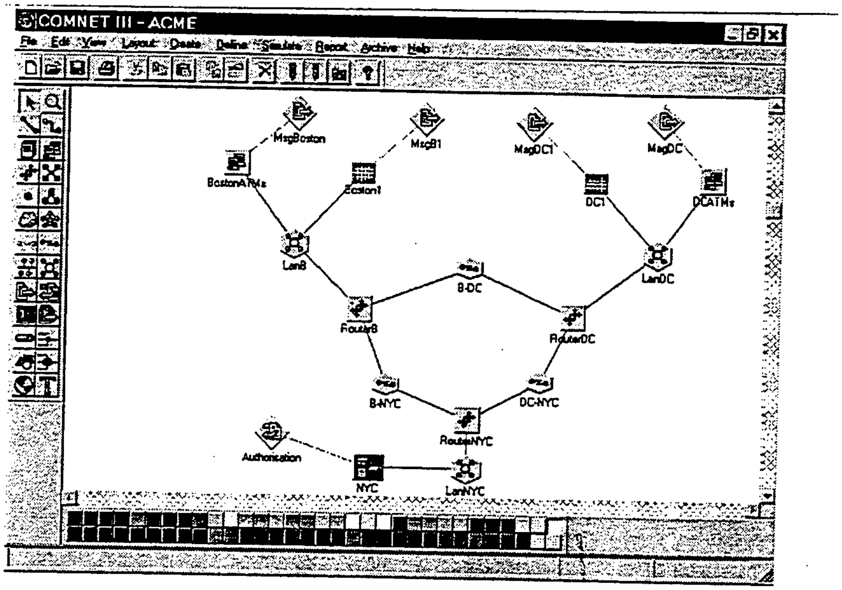


Figure 6.2 Comnet III Network Layout

These include:

(1) LAN, WAN & Internetworking systems.

(2) Circuit, message and packet switching networks.

(3) Connection-oriented and connectionless traffic.

(4) Static, adaptive and user-defined algorithms.

COMNET III is an object-oriented program. This fact allows it to abstract portions of a network model and treat them as modular components. Furthermore, the user is able to build a library of network components that can be "plugged in" and swapped at will.

The software package is available on most computer systems. These include many UNIX workstations and Personal Computers running Microsoft Windows, Microsoft NT, and OS/2. Each of these systems runs the same implementation of COMNET III. The only difference from one system to another is the appearance of the graphical user interface (GUI) due to different styles for windows, dialog boxes and other controls. The models that are built on one machine type can be moved to another machine type and run with identical results.

COMNET III is written in MODSIM II a high-level, object-oriented simulation programming language.

C. USES OF COMNET III

COMNET III is designed to estimate the performance characteristics of computing and communication networks. Estimating means that the network under study is described to the system via data. The program then executes a dynamic simulation of the network, which builds a computer representation of the network, and routes simulated traffic over it. Reports are produced on the measured performance of the different model elements and overall network characteristics, and are presented as the estimations of network performance.

This data, which is entered via a GUI, describes the following:

(1) The topology of the network: nodes, computer centers, connectivity, etc.

(2) The workload placed on the network. This includes the applications that rim on end systems and the traffic to be delivered across the network. The frequency and size of different tasks may be described statistically.

(3) The protocols for scheduling applications and routing traffic.

The reports produced are an estimate of the expected performance of the real network. Their accuracy is dependent on the data that has been entered to describe the network.

Another factor, which determines accuracy, is the run-length or amount of simulation time the model is run. The length of the run determines how many random events are used to represent the statistically generated traffic. COMNET III can run multiple, independent replications of the simulation and generate mean, maximum, minimum and standard deviations, as well as plots and histograms of system performance.

The goal of COMNET III is to provide the capability to include any network equipment type in the simulation. The user interface provides flexible interconnection of different devices so that you can describe your network to the system. It uses generic building blocks, which can be parameterized to represent the devices you want to model.

For every type of network to be modeled, the user has to pick the right level of detail in it, in order to answer the questions that are important. This is sometimes referred to as the *granularity* of the model. This aspect of modeling will greatly influence the degree of success of the simulation. If there is not enough detail the user may miss some important aspect of the system's behavior, while too much detail will lead to a model which is larger than needed and which takes longer to run than necessary each experiment.

Typical COMNET III applications include:

1. Peak Loading Studies

Generally a network is subject to heavy levels of traffic at particular times of the day, week, month or year. If the network design can cope with this level of traffic then it can cope with the workload during other periods. The typical use of COMNET is to model these peak-loading periods to gain an understanding of the stress points in the network.

2. Network sizing at the design stage

When designing a new network some provision for growth has to be allowed for. The software can be used to assess that the design meets current traffic levels, and it can be used to see what room there is in the design for system growth.

3. Resilience and contingency planning

It is often important to know that a network design has sufficient resilience to offer a reasonable level of performance in various failure scenarios. The nodes and link components in a model can be failed and recovered at various times in the simulation to test various contingencies that are not testable in the real system.

4. Introduction of new users/applications

New users and/or applications will typically add an extra load onto the network. It is useful to try and predict their impact before their introduction so that potential bottleneck can be identified and resolved before a major problem appears.

5. Evaluating performance improvement options

Many networks have year on year traffic growth. This results in deteriorating performance until the network is upgraded in some way. The various options for upgrading can be investigated in COMNET III as part of a cost vs. benefit study.

6. Evaluating grade of service contracts

It is increasingly common practice for service level contracts to be negotiated between the network user and the network provider, even when they are part of the same organization. COMNET III can be used to analyze the performance service levels that can be attained during contract negotiation, and to predict potential problem areas as usage patterns of network components change over time.

7. Academic purposes

The package is also available for academic purposes, since students can simulate network models. In this thesis the use of COMNET III will be used to the simulation of a wireless LAN.

D. SIMULATION CONTROL

After a model is ready for simulation, the commands under the Simulate menu may be used to control the simulation. The Verify command tests the model for correctness and completeness in terms of its being ready for simulation. This command is executed automatically before the simulation is started. However, while building a model, the user may use this command alone to test the current model for correctness without starting a simulation.

The Run Parameters Dialog is where the simulation experiment is defined. The Run Parameters include the replication time for the duration of the simulation for statistics collection, the warm up period when statistics are not collected, the number of replications for the number of reports and two checkboxes for resetting the system to empty-and-idle at the end of each replication and for running a warm up for each replication.

The Start Simulation menu item will start the simulation. This command first checks the current model to determine if it has been modified since the last save. If the model has

been modified, COMNET III presents a dialog box to give the user the option to re-save the model. Prior to starting the simulation, the program will verify the simulation to catch any errors in the model before the simulation starts. After the model has been saved and verified, the simulation will begin.

Before or during the simulation, the Animate and Trace menu items are available for setting the parameters for animation or for tracing. Animation parameters include switches for the animation and the clock as well as a field for the token speed. During the simulation with animation on, tokens representing the frames are shown entering the link and packets leaving a link. Furthermore, numbers may appear above nodes representing numbers of sessions established on the item, percent utilization and other similar information.

Trace parameters include switches to trace to the screen or to a file. When tracing to the screen, there is a choice to delay the trace message for a period of time or to single step with a button to step to the next event. The trace messages are for high-level events down to the packet level. These events include application triggering, command execution and packet actions, but generally not at the frame level. When tracing to the screen, packet traffic will highlight the node where the event is occurring in green and call events are highlighted to show the circuit that is either established or blocked.

Finally, there is the Memory Usage menu item that is useful for monitoring the number of objects allocated by COMNET III and how much memory is used. When this item is selected, COMNET III writes a file named "memstat.txt" to the working directory. This file is useful for identifying whether the model is running out of RAM and for checking to see what aspects of the model are using the most memory.

VII. WIRELESS LAN SIMULATION

In this chapter we simulate a wireless LAN that consists of five identical computers: Gemini, Aries, Leo, Scorpio and Libra. The purpose is to test the performance of the new wireless LAN link (CSMA/CA), under different load situations, described later on this chapter. The modulation technique proposed for this specific type of model is the Frequency Hopping Spread Spectrum (see Chapter 5). Figure 7.1 shows the simulated network.

We make no assumptions on what applications are running, in order to get more general results. The number of replications, the duration of simulation and the use of warm up period, either in the beginning or before each new replication can also affect the findings of the simulation. For the model we used one replication of 60 seconds.

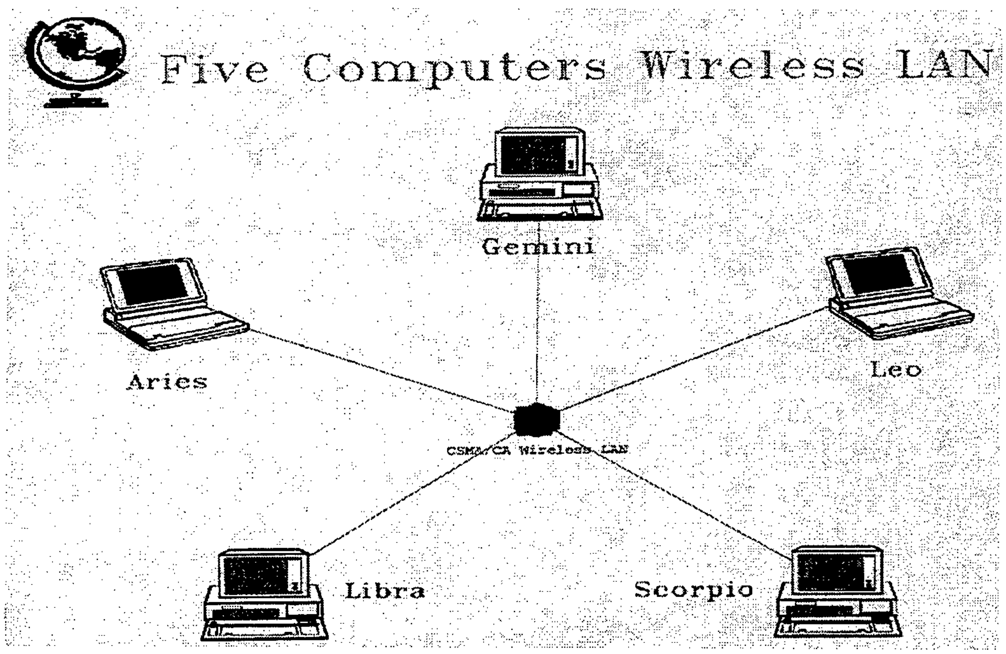


Figure 7.1 Five computers Wireless LAN

A. NETWORK LOAD

The way selected for adding traffic in the model is the Packet Rate Matrix (PRM). This matrix allows the user to directly generate packet traffic, without scheduling applications and without producing messages with transport commands. Such a mechanism is useful when a user knows the packet rates and sizes, for the network. Each packet flow has an origin, a destination, a packet inter-arrival time and size distribution, application and protocol. In this case, the application and protocol types are used solely for reporting purposes and they do not affect packets scheduling. The PRM settings are summarized in Table 7.1.

Table 7.1 PRM Settings

	Entry 1	Details/Remarks
Origin	Machine 1	
Destination	Machine 2	
Application Type	Other	
Protocol	Generic	Library Selections
Load (pps)	Various	See Table 7.2
Inter-arrival Time (sec)	Exponential	See Table 7.2
First Arrival Time (sec)	Exp(1.0)	
Last Arrival Time (sec)	None	
Packet Size	1000 bytes	See Figure 7.2
Priority	1	

In order to test the CSMA/CA performance we use different loads. Each of the five stations generates a number of packets per second. Moreover, each station is designed to send and receive the same number of packets to and from all the other stations. The load, namely the total number of packets per second, used in the simulation varies from 10 to 400. The packet size is chosen to be constant, namely 1000 bytes. The arrival of the first packet is an exponential distribution, shown in Figure 7.2, with a mean value of 1.

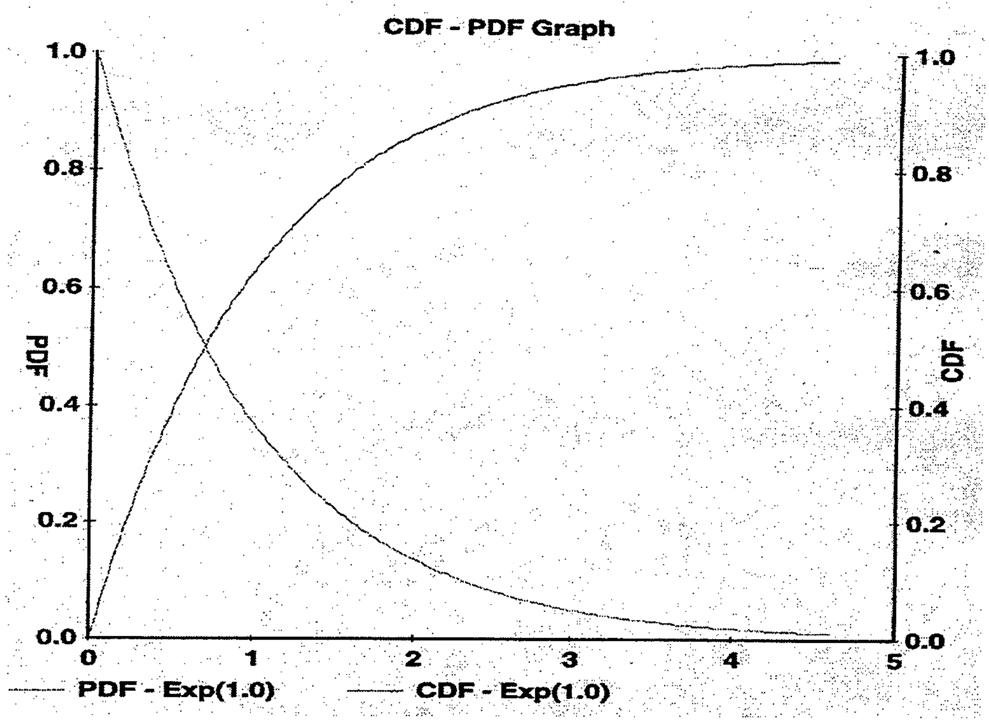


Figure 7.2 The first packet arrival time distribution

This distribution is widely used to model arrival times of events, which follow a Poisson pattern. Each sample chosen form the exponential function specifies the time which elapse before the next arrival. Samples have a high probability of being less than the mean, which in our case is one. This implies that the distribution has a long tail and will occasionally provide a sample significantly higher than the mean. This behavior is very useful in modeling random arrival patterns.

The last packet arrival time does not have to be specified, but the time period of the simulation is 60 seconds. The packet inter-arrival time is an exponential distribution but the mean value differs with the network load. Table 7.2 shows the different packet inter-arrival distributions.

Table 7.2 Load and Inter-arrival Time

Load (pps)	Inter-Arrival Time
10	Exp(2.0)
20	Exp(1.0)
40	Exp(0.5)
60	Exp(0.3333)
80	Exp(0.25)
100	Exp(0.2)
200	Exp(0.1)
400	Exp(0.05)

B. LINK PARAMETERS

The link protocol used for the Medium Access Control (MAC), is the new standard of IEEE 802.11, the CSMA/CA. This protocol is discussed in Chapter V.

1. Protocol Parameters

The most important parameter of the protocol is the *data rate*, namely the number of the bits per second supported by the 802.11 wireless LAN physical medium. The model uses the 1 Mbps data rate. Another input is the *propagation delay*. For a maximum distance of 150 m, the propagation delay based on the speed of light is 0.5 microseconds. Furthermore, the user has to specify the *interframe gaps* or according to the CSMA/CA terminology, the Short and Distributed Interframe Spaces. This setting is also used to update the backoff interval in the shared medium access algorithm. For the particular model, a value of 18 microseconds will be used.

The Short Inteframe Space is the shortest of the interframe spaces defined in IEEE 802.11. It is used to provide an efficient MAC Service Data Unit (MSDU) delivery mechanism. Once the medium is seized, the station will keep it for the duration of the frame exchange it has to perform. In the implemented model, the Short IFS is used between fragments of one MSDU and their ACK frames. Using the smallest gap between transmissions within the frame

exchange prevents other stations, which are required to wait for the medium to be free for a longer gap (the Distributed IFS, see below) from attempting to use the medium, thus giving priority to completion of the frame exchange in progress. In the model a value of 7 microseconds is used.

The Short IFS (SIFS) is also used to compute the Distributed IFS (DIFS) based on the following equation:

$$\text{Distributed IFS} = \text{Short IFS} + (2 * \text{Slot Time}) \tag{7.1}$$

The DIFS is used by the CSMA/CA model to contend for the channel for initial frame transmissions. A station is allowed to transmit if it detects the medium to be free for the DIFS duration and its backoff time has expired.

Frame maximum length and *overhead* are two additional inputs for the simulation. For the specific application, a Poison distribution with mean value 1000 bytes is used for the frame length, while the value used for the overhead is 42 bytes.

The *fragmentation threshold* specifies the current maximum size, in bytes, of the Mac Protocol Data Unit (MPDU) that will be delivered to the physical layer. The used value is 1200, which is 200 bytes above the mean value of the selected Poisson distribution for the frame size. Fragmentation creates MPDUs smaller than the MSDU (frame) size to increase reliability by increasing the probability of successful transmission of the MSDU (frame) in cases where channel characteristics limit transmission reliability for longer frames. When a frame is received with MSDU size greater than the specified "Fragmentation Threshold," the frame must be fragmented. The MPDUs (or fragments) resulting from the fragmentation of an MSDU are sent as independent transmissions, each of which is separately acknowledged. This permits transmission retries to occur per fragment, rather than per MSDU (frame). Unless interrupted due to medium occupancy limitations for a given physical system, such as a dwell time boundary in a Frequency Hopping Spread Spectrum (FHSS) system, the fragments of a single MSDU are sent as a burst, using a single invocation of the CSMA/CA medium access procedure. In other words, once the station has contended for the channel, it will continue to send fragments (by using the Short Interframe Space instead of the Distributed Interframe

Space) until either all fragments of a MSDU have been sent, an acknowledgment is not received for directed data due to collision or transmission error, or the station can not send any additional fragments due to a dwell time boundary. Should the sending of the fragments be interrupted due to one of these reasons, the frame or the fragment will enter a retransmission backoff period; when the next opportunity for transmission occurs the station resumes sending the rest of the fragments of the frame.

The next parameter used is the *fragment error probability*. This parameter specifies the error rate of transmitting one fragment over the physical medium. For the simulation we assume that this probability is zero.

Acknowledgment (ACK) timeout specifies the length of time by which an ACK frame should be received in response to transmission of a frame that requires acknowledgment. It is timed from the instant that the transmitting station finishes the transmission of the frame or fragment. The reception of a unicast frame (or fragment in the case where fragmentation is needed) requires the receiving station to respond with an ACK frame, if the received frame (fragment) is correct. Lack of reception of an expected ACK frame indicates to the source station that an error has occurred and causes the station to retransmit the frame (or fragment). An erroneous ACK frame causes the retransmission of the transmitted frame (or fragment) as well. The transmission of the ACK frame commences after the Short IFS without regard to the busy/free state of the medium. The ACK Timeout may not be less than:

$$2 * \text{Propagation Short IFS} + \text{Ack Transmission Time}) \qquad (7.2)$$

The *acknowledgment error probability* specifies the error rate of transmitting an ACK frame over the physical medium. An ACK frame is 14 bytes long. For the simulation we assume that this probability is zero.

Another setting is the *frame transmission lifetime*, which is defined as the elapsed time, after initial transmission of an MSDU, after which further attempts to transmit the MSDU will he terminated. The selected value is 512 milliseconds.

Since the transmission technique of Frequency Hopping (FHSS) is selected, one should specify the *Dwell Time*. This parameter is defined as the time the physical medium

dependent system can dwell on a FH channel and meet the requirements of the current regulatory domain. In the implemented CSMA/CA model, the FH dwell time is used for determining if the station can retain the control of the channel during the process of transmitting fragments of an MSDU. Once the dwell boundary is up, the frame has to enter the backoff period and contend again for the channel. A value of 1000 seconds is used for the dwell time parameter. Table 7.3 summarizes the values of the parameters used in the model.

Table 7.3 Parameter values for the CSMA/CA

Parameter	Selected value
Data Rate	1 Mbps
Propagation	0.5 microseconds
Slot Time	18 microseconds
Short IFS	7 microseconds
Frame max	1200 bytes
Frame OH	42 bytes
Fragmentation Threshold	1200 bytes
Fragment Error Probability	0
ACK Timeout	0.125 msec
ACK Error Probability	0
Frame Transmission Life Time	512 msec
Frequency Hopping Dwell Time	1000 sec

2. IEEE 802.11 Backoff

This part of the dialog box provides a group of parameters for the backoff algorithm. A station that desires to initiate transfer of data and finds the medium busy follows the backoff procedure. To begin the backoff procedure, the station selects a backoff time based on the following equations:

$$\text{Backoff Time} = \text{INT}(\text{CW} * \text{Random}()) * \text{Slot Time} \tag{7.3}$$

Where:

CW = An integer between the values of CW min and CW max

Random () = Pseudo-random number between 0 and 1

Slot Time = The value specified above

The Contention Window (CW) parameter takes an initial value of the CW min for every MPDU queued for transmission. The CW will take the next value in the series at every retry to send a particular MPDU until it reaches the value of the CW max. The set of CW values are 7 (CW min), 15, 31, 63, 127, 255 (CW max).

The parameter "Retry limit" indicates the maximum number of retransmission attempts of a fragment. It is set as the default value 7. Once this limit is reached, a failure condition is indicated to the next higher layer. Note that the statistics report on "Number of tries to resolve" may have a bigger value than this parameter. This is because the statistics held is on frame basis while the retry limit in the implemented CSMA/CA is on fragment basis.

All backoff periods occur following a DIFS period during which the medium is free. A station in backoff monitors the medium for carrier activity during backoff periods. If no carrier activity is seen for the duration of a particular slot, then the random backoff process decrements the backoff timer by Slot time specified above. If there is carrier activity sensed at any time during a backoff period, then the backoff procedure is suspended; that is, the backoff timer will not be decrement for that slot. The medium must be sensed as idle again for the duration of a DIFS before the backoff procedure is allowed to resume. Transmission commences whenever the backoff timer reaches zero.

A station that had just transmitted an MSDU and has another MSDU ready to transmit will perform the backoff procedure in order to produce a level of fairness of access to the medium amongst stations.

Some of the performance measures on the output reports have special interpretations for CSMA/CA links. On the Channel Utilization report, the column for FRAMES RST/ERR shows a count of the number of frames that reach the Retry Limit or the XmitLifeTime. On the same report utilization does not include the time required for transmissions in error. On

the Collision Stats report, NBR OF TRIES TO RESOLVE includes retransmissions due to both collisions and errors. Table 7.4 shows the values of the parameters used in the backoff algorithm.

Table 7.4 Parameter values for the Backoff Algorithm

Parameter	Selected Value
Contention Window Minimum	7
Contention Window Maximum	255
Retry Limit	7
Session Limit	1024

C. REPORTS

The reports selected to present the outputs for the model are: Channel Utilization, Collision Statistics and Packet Delay. All the reports showing the simulation results are presented in the Appendix B.

1. Channel Utilization

In this report one can see the number of the frames removed from the output buffer at the transmitting node on the link and subsequently placed in the input buffer of the receiving node. Frames that are in transmission when the report is produced (because of transmission delay and propagation delay) are not reported.

Furthermore, on a link, a framing error probability may be specified which causes statistically picked frames to be retransmitted as if they were in error. The number of retransmitted frames is reported.

Another useful output in this report is the transmission delay. It is the time between when the frame (which may be part of a packet or contain several packets) is created at the input to the link and when the frame is delivered at the end of the link. It includes transmission, contention-resolution and propagation time. The average, the standard deviation and the maximum delay are reported.

Finally, the most important output is the channel utilization. The transmission time for a frame is calculated from its size divided by the link speed. The link is in use for this time plus the propagation delay across the link for each frame. Utilization is then reported as the total usage time in the simulation run divided by the simulation run length.

2. Collision Statistics

This report presents how many times a collision occurred on the link, that is when two or more nodes try to transmit inside the same collision window. Moreover, it shows the total number of frames involved in collisions. When a collision occurs, each colliding frame has to be retried at some later time. The retry frame may also collide. From the point of view of the first frame in the retry sequence, the report presents the average, the standard deviation and the maximum number of retries attempted before successful transmission.

If a node attempts to transmit a frame and sees the link busy, it defers its transmission until the link becomes idle (plus the contention interval). The report shows how many transmission attempts had to be deferred. Moreover, one could see the average, standard deviation and maximum delay, due to transmission deferral that is observed in the simulation, along with the number of frames queued in buffer.

Now, when a collision occurs in the collision window, it may be between two or more frames arising from different nodes. The simple case is between just two frames, but in a heavily congested system it is possible that frames from more than two nodes are involved in the collision. There is a part of the statistics showing the number of episodes where more than two frames are involved.

3. Packet Delay

In the simulation we did not select a specific type of application or a transport layer protocol Therefore the corresponding fields of the report should read "other" and "generic" respectively. Furthermore we can see how many packers have been created to send to the listed destination and how many packets have been received. This may differ from the number of packets created by the number of packets that are in transit at the instant the report is written.

Packets may be retransmitted from the origin because they are blocked at some point en route to the destination. Blocking can occur because input or output buffers are full, or because a node or link on the route fails. In this simulation no packets are retransmitted, since we assumed no failure. Nevertheless, when a node or link fails, the user can specify whether the transmission should be re-attempted. If no retransmission is specified then the packet will be dropped and reported here.

The time between creating a packet on the originating node and the time of receiving the packet at the destination node, in milliseconds, averaged over all packets sent during the simulation, can also be seen in this report, along with the worst case packet delay, in milliseconds.

D. SIMULATION RESULTS

1. Channel Utilization

In this section we focus on the statistics for the channel utilization. In Table 7.5 we see the channel utilization under different loads. The protocol tested is a carrier sense multiple access with collision avoidance. Therefore, we expect some similarities with the channel utilization of the networks using CSMA/CD. In Figure 7.3, we see the graph corresponding to Table 7.5.

Table 7.5 Channel Utilization for CSMA/CA

Load (pps)	Utilization (%)	Remarks
10	08.85	
20	16.39	See Figure 7.5
40	34.34	
60	48.91	See Figure 7.6
80	66.12	
100	75.60	See Figure 7.7
200	74.64	
400	75.16	See Figure 7.8

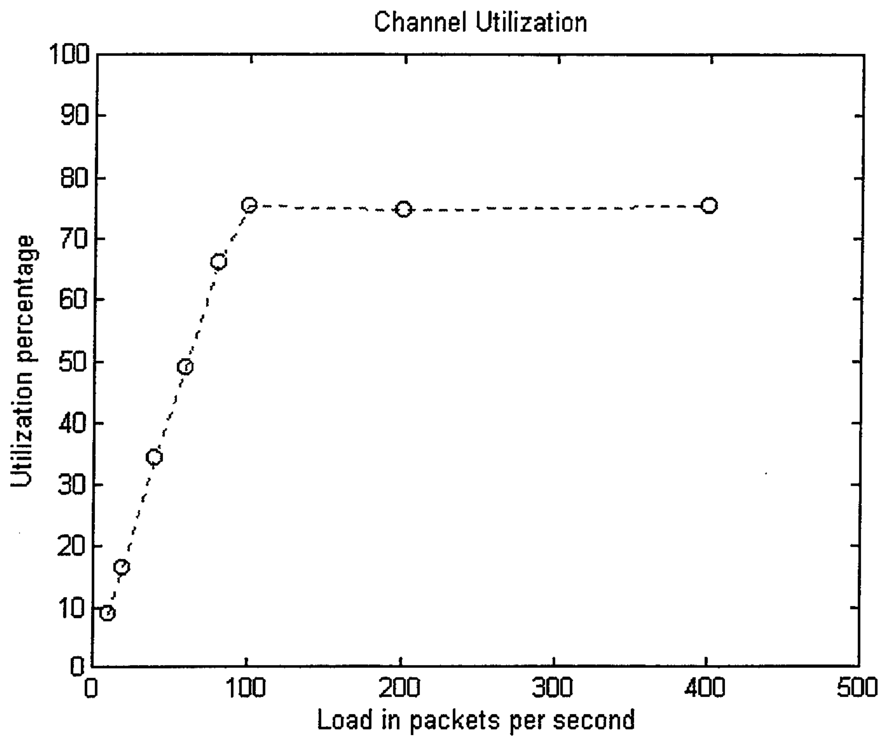


Figure 7.3 Channel Utilization: Actual Data

As expected, the channel utilization increases with the load and reaches a high value of approximately 75% for 100 packets per second. During this period, we have practically no collisions. Above the 100 packets per second, the utilization remains constant, but the collision episodes increase drastically with the load. The simulation program does not allow experiments for loads that exceed the 400 packets per second. It returns a system error due to the high congestion of the network. Therefore we assume that above 400 packets per second, the utilization eventually drops, due to the high percentage of collisions. The fact that the utilization was stable at a significantly high percentage could be explained by the collision avoidance algorithm. In Figure 7.4 we see a projection for the overall channel utilization.

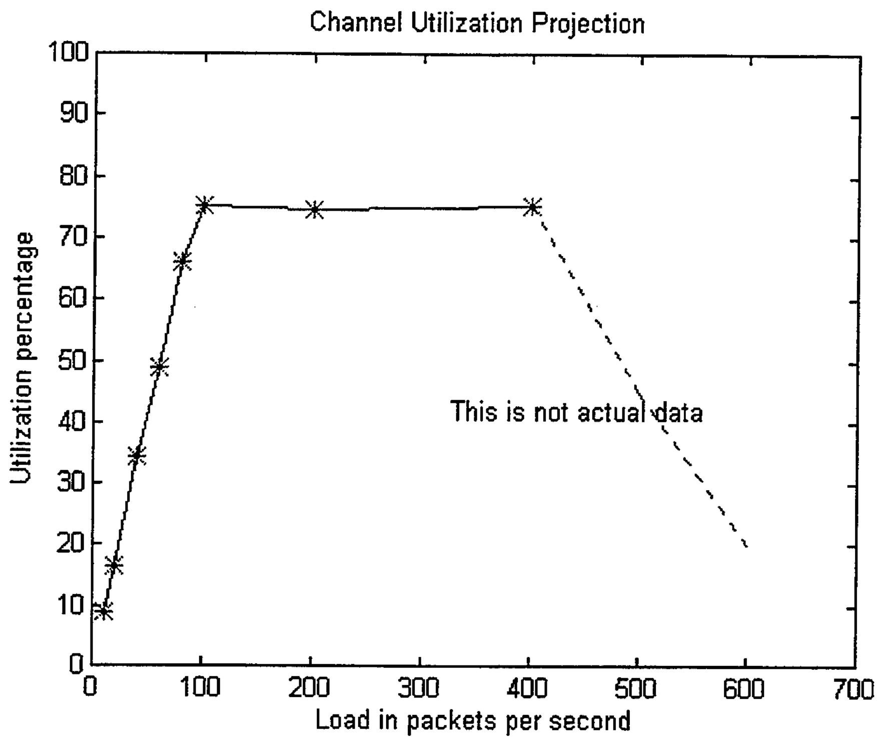


Figure 7.4 Overall Channel Utilization

Figures 7.5 to 7.8 show the channel utilization as a function of time, for some characteristic loads.

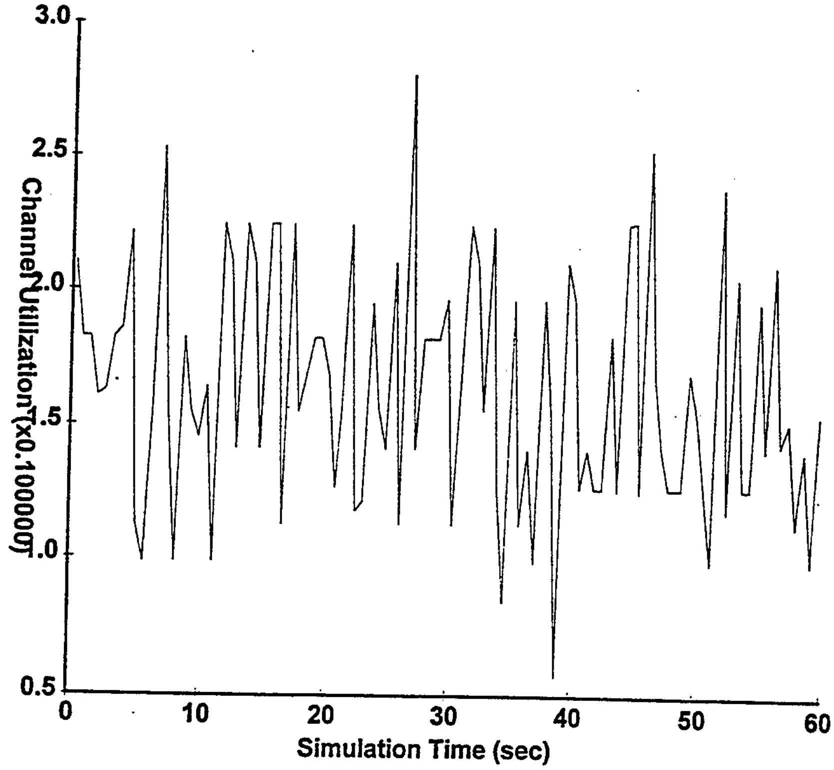


Figure 7.5 Channel Utilization: 20 packets per second

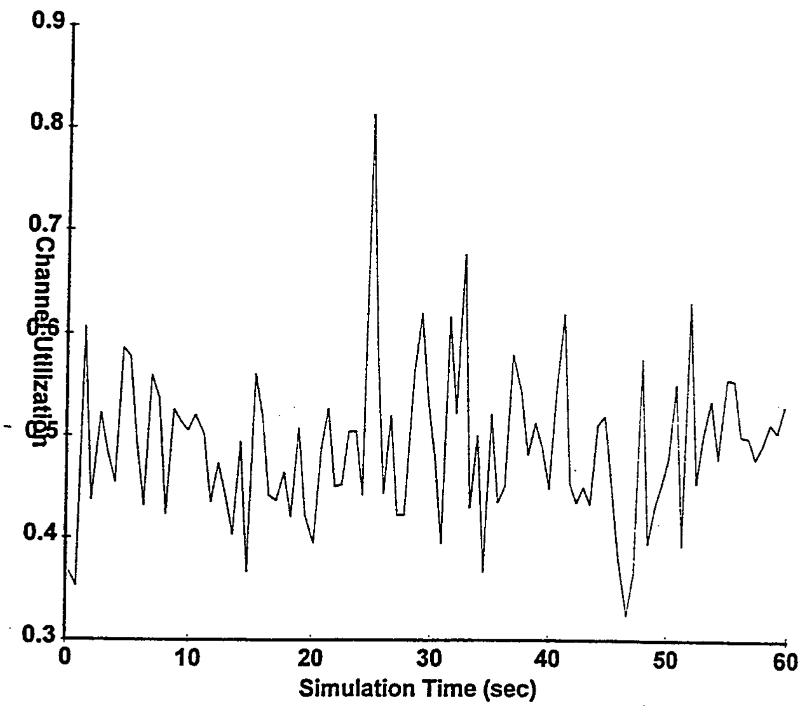


Figure 7.6 Channel Utilization: 60 packets per second

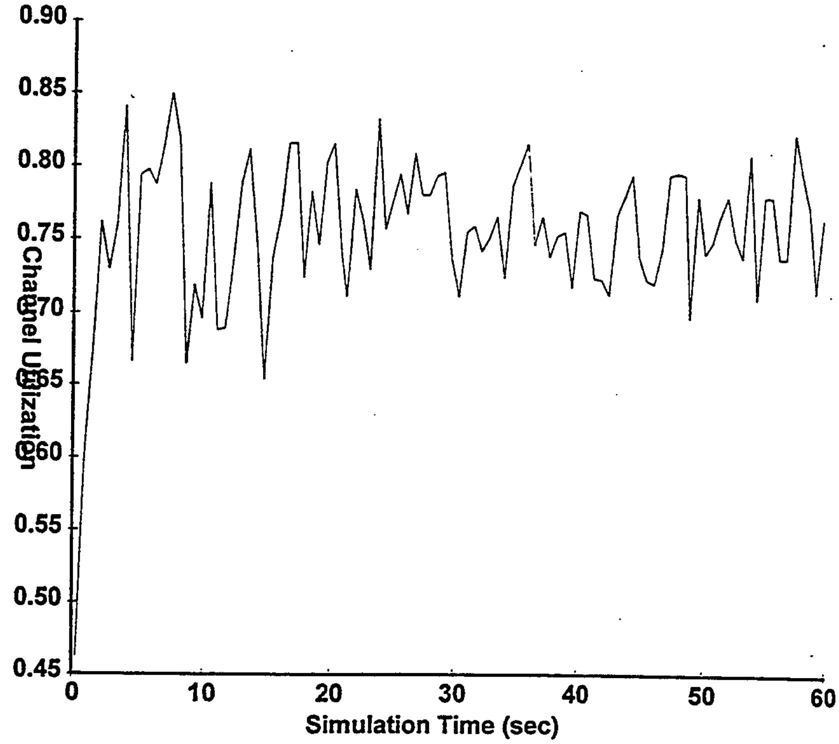


Figure 7.7 Channel Utilization: 100 packets per second

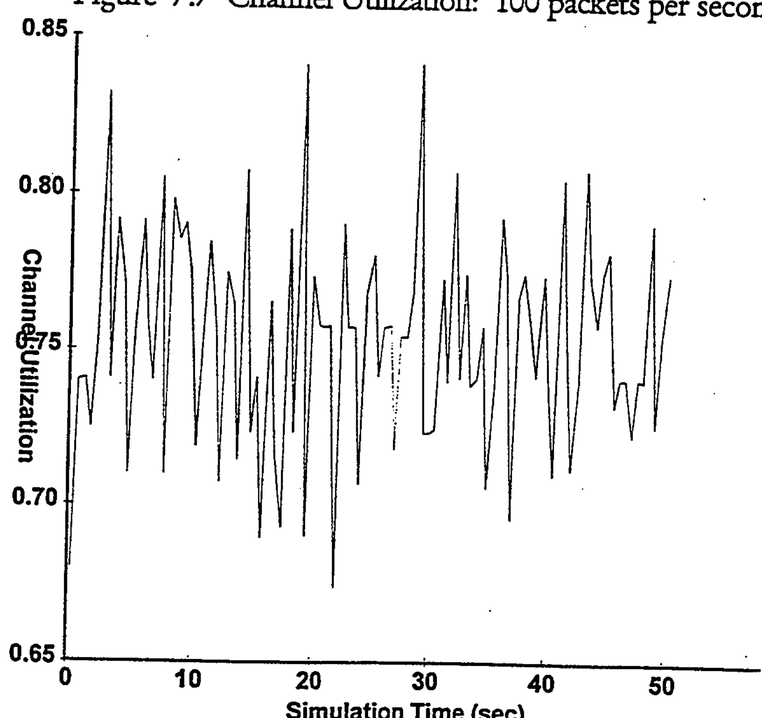


Figure 7.8 Channel Utilization: 400 packets per second

2. Packet Delay

Table 7.6 shows the average packet delay, under various network loads. More details about the number of packets created in each station and the corresponding delays can be found in Appendix B. Figure 7.9 shows the graph that corresponds to Table 7.6. Furthermore, the packet delay as a function of time, for some characteristic loads, is shown in Figures 7.10 through 7.13.

Table 7.6 Packet Transmission Delay

Load (pps)	Average (ms)	Standard Deviation (ms)	Maximum (ms)	Remarks
10	8.762	1.265	22.688	
20	9.238	2.578	32.749	Figure 7.10
40	10.811	6.054	83.794	
60	13.234	11.314	221.807	Figure 7.11
80	17.608	18.649	242.958	
100	47.130	79.703	519.812	Figure 7.12
200	55.047	86.122	519.889	
400	54.908	87.025	520.025	Figure 7.13

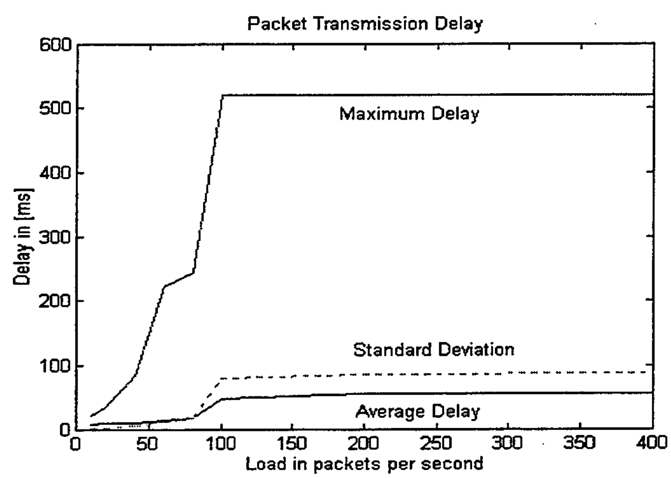


Figure 7.9 Packet Transmission Delay

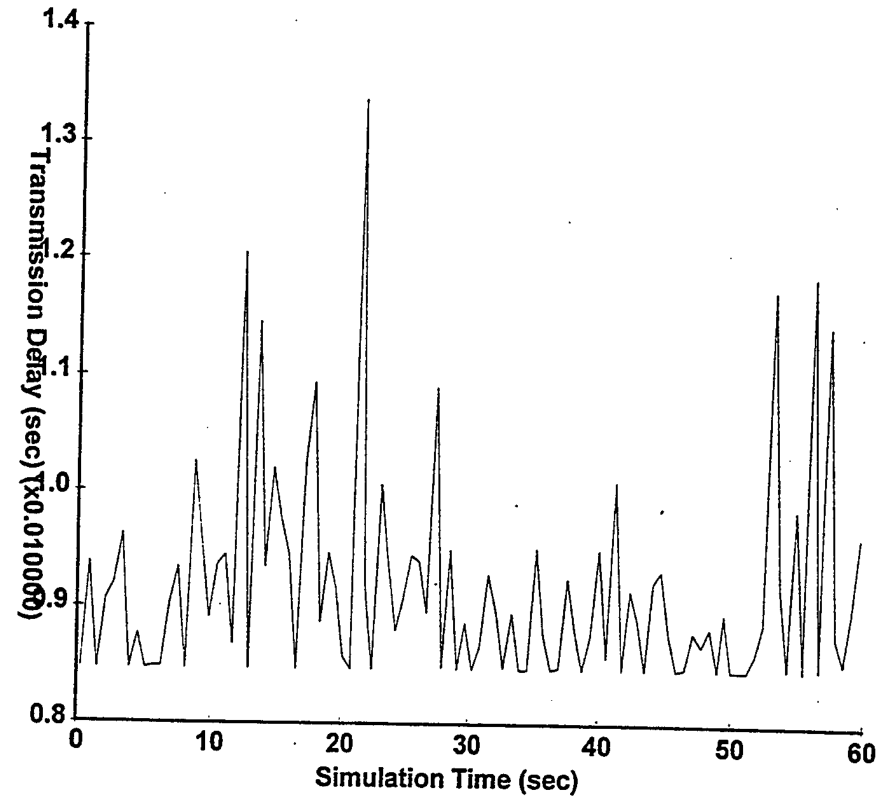


Figure 7.10 Frame Delay: 20 packets per second

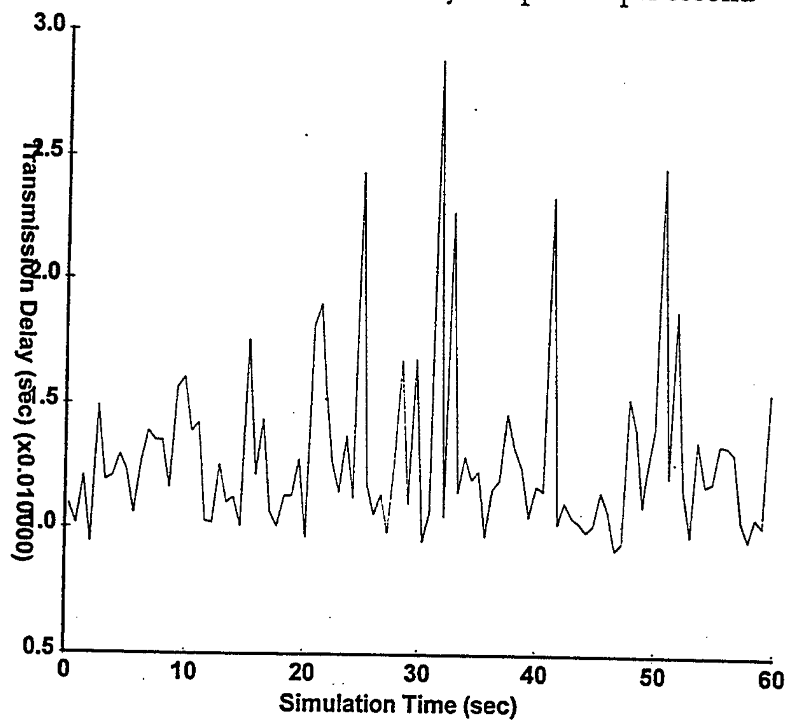


Figure 7.11 Frame Delay: 60 packets per second

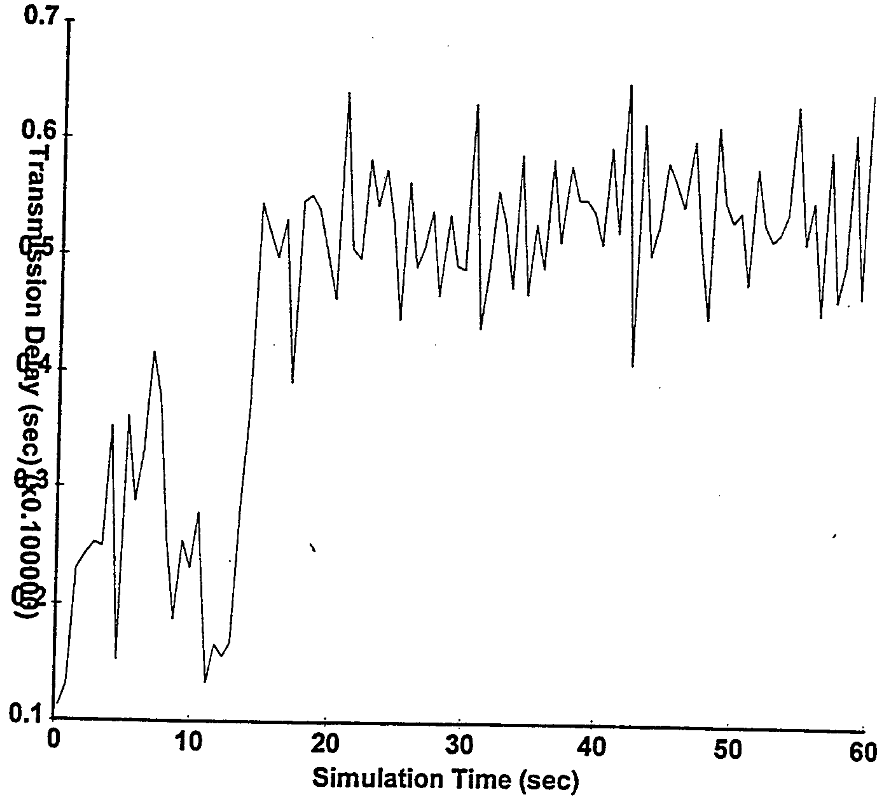


Figure 7.12 Frame Delay: 100 packets per second

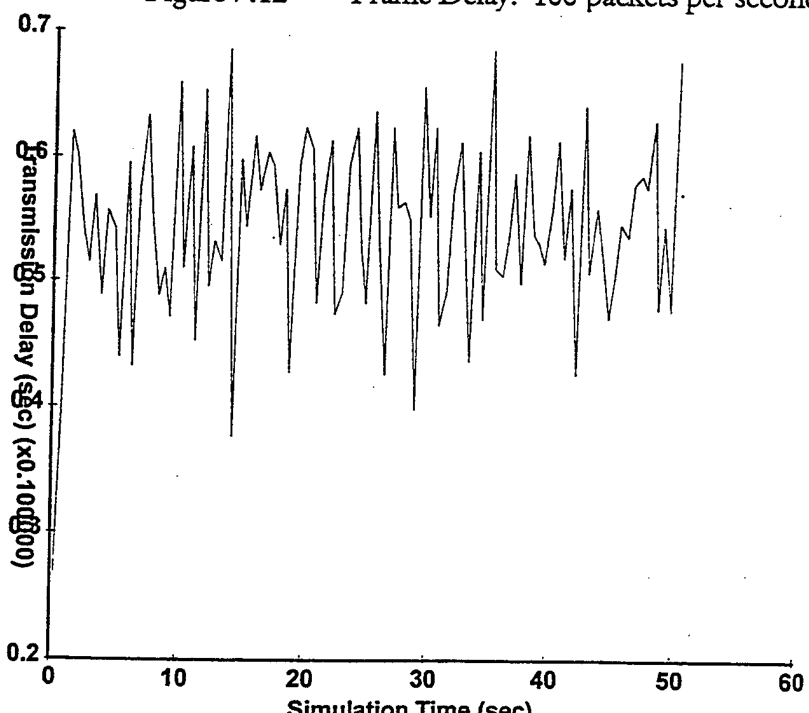


Figure 7.13 Frame Delay: 400 packets per second

E. SIMULATION CONCLUSIONS

In this section we present some conclusions about the behavior of the IEEE's 802.11 standard for the medium access control layer. One should take into consideration that our conclusions are based upon the simulation results, which may be different if certain parameters are changed. These parameters have to do with the link configuration more than with the simulation setup, since we run the simulation with several different configurations without observing significant variations in the outputs.

Another interesting point is the selection of the network load. We simulated a wireless local area network that consists of five identical working stations. Each one sends and receives the same number of packets per second, to and from every other station. Moreover, we used the Poisson distribution to describe both the first packet arrival time and the packet interarrival times. We think that this is the most realistic way to represent a wireless local area network load. Nevertheless, the simulation results may slightly vary if we select other distributions. For example, using a constant packet interarrival time gives a channel utilization of 1% higher.

Finally, we present the channel utilization and the packet transmission delay, as the most characteristic parameters of a wireless local area network's behavior. One should use these outputs in conjunction with other reports and link statistics to obtain an even more detailed idea about the CSMA/CA performance.

The main conclusion is that although the tested protocol is a carrier sense multiple access, it does not perform as far as the channel utilization is concerned, like the CSMA/CD. Figure 7.3 shows an increase of the utilization percentage with the load. The difference with other CSMA protocols is that the utilization stabilizes in a high percentage for a wide range of loads. We assume that this fact is due to the collision avoidance algorithm. Moreover, there is no typical utilization decrease. Instead of that, the network becomes overloaded after a certain load and the simulation program returns an application error. Nevertheless, we can safely assume that the overall channel utilization looks like the graph in Figure 7.4.

To be more precise, in Figure 7.6 we see that for a load of 60 packet per second although the channel utilization is about 50% in average, we reached a high of 80% without having any collisions at all. In Figure 7.7 the channel utilization stabilizes at an average of 75%. At the same load the average packet delay, given in Figure 7.12, increases with time and is

about 47 ms in average, while delays of 519 ms can be observed. This is the turning point for the network, since we see in the output reports (Appendix B), that we have an increase in the collision episodes and some packets are dropped.

On the other hand, one can tell from Table 7.6 that for loads above 80 packets per second, the transmission delay increases drastically. Given that the channel utilization for this load is 66% (see Table 7.5), one can conclude that the optimum load range for the CSMA/CA in the simulated wireless local area network, is from 80 to 200 packets per second. Above that the channel utilization is still high (approximately 75%), but the packet transmission delay and the packet collisions increase with the load. Nevertheless, the simulation proved that the CSMA/CA link can be used for loads up to 400 packets per second. Above that, the network is overloaded. Note that when we refer to the network load we mean the total load. For example for a load of 100 packets per second, each working station contributes 20 packets.

To sum up, the new standard for the wireless local area network is reliable under certain load conditions. Although the collision avoidance mechanism does not eliminate the collisions, it keeps the channel utilization high and stable for a wide range of loads. Collisions still occur, but the number of episodes is small when the network is not overloaded. This fact makes the medium access control protocol reliable for the proposed computer communications.

VIII. CONCLUSIONS

In this final chapter, we present the conclusions of the research, for both the physical and the medium access control layers of the wireless local area network communications.

This research focused on the development of a wireless local area network on which the new IEEE's 802.11 working group standard is applied and tested. In the physical layer, a model of a transmitter and a receiver system was used to demonstrate the signal strength problems caused by multipath interference. This model investigates the worst case signal-to-noise ratio in the receiver, created by the interference of two waves transmitted from a point source. The first one travels on a straight line connecting the transmitter and the receiver and the second arrives at the reception point after reflection. In the medium access layer, a simulation of a wireless local area network investigates the behavior of the new standard's protocol, under different network loads.

The objective of this thesis was to propose a realistic and applicable physical model, that can be used in a wireless local area network and to investigate the reliability of such a network, by implementing the IEEE 802.11 CSMA/CA MAC protocol. For the purposes of this thesis, this stand-alone local area network consists of five working stations, operating outdoors in a separation distance of approximately 100 meters.

In the physical part, the methodology is just as important as the result. The worst case signal-to-noise ratio that we found is based on the interference of two rays. In our model, only one ray is reflected, creating interference problems at the receiver. In a more realistic model, several reflections should be taken into consideration. The more details one can provide about the area in which the network operates, the closer to a real world multi-path interference prediction one can be. Nevertheless, the principles are the same and the equations derived for the creation of our model can be expended to include such cases, as mentioned in Chapter III.

Moreover, the Matlab programming code for this model, presented in Appendix A, does not limit the user in a specific set of parameters. One can select one's own set of values for the model parameters, including the atmospheric attenuation factor, for example, at different frequencies. Finally, the code can be easily modified, based upon the equations that

we derive in Chapter III, to account for more reflected rays from obstacles in various distances.

The main conclusion from the physical part is that the data rate values that the COMNET III simulation software assumes are valid and realistic. Moreover the proposed by the standard's physical layer, 1MGz bandwidth, for receivers that implement the Frequency Hoping Spread Spectrum modulation technique, is realistic and in accordance with the worst case signal-to-noise ratio that we found. The maximum channel capacity that our model predicts, is 2.6 Mbps and the standard supports either 1 or 2 Mbps.

Finally, the other important output from the transmitter- receiver model simulation, the propagation delay, is one of the main inputs for the wireless local area network simulation of the second part. This parameter along with the data rate is the connecting bonds between the two parts of the research.

In the medium access control part, we tested the IEEE's 802.11 working group, wireless local area network standard, the CSMA/CA. With a set of parameters, both for the protocol and for the simulation, we applied this standard to a wireless local area network that consists of five working stations. We found that the protocol is reliable for wireless computer communications, since we tested it under different loads.

As mentioned in details in Chapter VII, for our model the optimum load range for the specific network is from 80 to 200 packets per second, while the collision avoidance algorithm accounts for the significantly limited number of collision episodes in that load range. One should notice that although this protocol is a carrier sense multiple access one, it behaves in a different way than the similar protocols for the wired networks do.

SUGGESTIONS FOR FUTURE WORK

In the first part, a continuation of this thesis could be the simulation of a wireless local area network that operates under specific area limits. For example, the development of a transmitter – receiver model that operates indoors in the same or higher frequencies. In such an environment, the number of ray bounces from the walls is more than one. For such a model, several modifications in the programming code should be done.

For the testing of the IEEE's standard for wireless local area networks, there is a great

variety of proposed scenarios. For example, the simulation of a wireless local area network that consists of either smaller or bigger number of working stations placed at distances less than 100 meters, could be a suggestion. The load range applied to such a network may be the same or different from one we used, and the simulation settings could vary. Finally, a comparison of the performance of the several wired network protocols, in a wireless local area network, could be an interesting research. For all the above suggestions, the existing simulation programs, such as the CACI COMNET III, are sufficient and we expect that the results are realistic and reliable.

APPENDIX A. MATLAB CODE

A. PROGRAM 1

```
% Ltjg E. D. Kyriakidis
% Hellenic Navy
% -------------------------
%
%        ****************************************************
%        ** noattre.m - MODEL WITH NO ATTENUATION **
%        ****************************************************
%
% This program calculates the irradiance I as a function of distance  of the reception point,
% for one wave travelling in the Line Of Sight, two rays (one reflected) and their ratio.
% The attenuation factor has not been taken into consideration.
%
% Default Values for the problem:
% ---------------------------------
% a) Frequency                                      f = 2.4 GHz
% b) NO Attenuation
% c) Wall Distance for the transmitter              ht = 10 m
% d) Wall Distance for the receiver                 hr = 2 m
% e) Permittivity                          eo = 8.8542E-12 Cb2 N-1 m-2
% f) Electric field amplitude in 1m from the source   Eo = 1 V
% g) Speed of light                                  c = 3E-8 m/sec
% h) Reflectivity 10%                               G = 0.1
% i) The distance varies                            2 m - 500 m
% k) For plotting the data pairs are                3000

%------------------------------------------------------------------
```

```
st=input('To run the model with the default values press 1.
         To give your parameters, press 2:');
if st==1;

%          ***************************************************
%          ** DEFAULT VALUES FOR THE MODEL **
%          ***************************************************

f=2.4E9;
ht=10;
hr=2;
d=linspace(2,500,3000);
Eo=1;
G=0.1;
eo=8.8542E-12;
c=3E8;
w=2*3.1416*f;
t=1/w;                               %   evaluated at t=1/w
K=(2*3.1416/3E8)*f;

%          **********************************
%          ** Geometry considerations **
%          **********************************
d1=sqrt(((ht-hr)^2)+(d.^2));
d22=sqrt((((ht-hr)^2)+(d.^2)+(4*hr*(ht-hr)))/(((ht/hr)+1)^2));
d21=(ht/hr).*d22;
d2=d21+d22;
a1=K.*d1;
a2=K.*d2;
```

```
%           ****************************
%           ** LOS only (figure 1,2) **
%           ****************************
E1=Eo./d1;                      % E1 is the amplitude in V/m
E=E1.*sin((w*t)-a1);            % E is the magnitude
figure(1);
plot(d,E);
axis([2 300 -0.14 0.14])
title('T/X - R/X System: LOS - NO Attenuation')
xlabel('Distance d in [m]')
ylabel('Electric Field E in [V/m]')

I1=0.5*eo*c*(E1.^2);
figure(2);
plot(d,I1);
axis([2 120 0 2E-5]);
title('T/X - R/X System: LOS - NO Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')

%           ****************************************
%           ** 2-ray path. Reflection (figure 3,4) **
%           ****************************************
E2=G.*Eo./d2;
Eot=sqrt((E1.^2)+(E2.^2)+(2.*E1.*E2.*cos(a2-a1)));
a=atan(((E1.*sin(a1))+(E2.*sin(a2)))/((E1.*cos(a1))+(E2.*cos(a2))));
Et=Eot.*sin((w*t)-a);
I2=c*eo*0.5*(Eot.^2);
```

```
figure(3)
plot(d,Et);
axis([2 400 0 0.12])
title('T/X - R/X System: 2-ray path - NO Attenuation')
xlabel('Distance d in (m)')
ylabel('Electric Field E in [V/m]')

figure(4)
plot(d,I2);
axis([2 100 0 2.2E-5]);
title('T/X - R/X System: 2-ray path - NO Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')

%               ******************************
%               ** Ratio of the Irradiances **
%               ******************************
RI=I2./I1;
figure(5)
plot(d,RI);
axis([2 500 0.8 1.22]);
title('Ratio of Irradiance. NO Attenuation.')
xlabel('Distance d in (m)')
ylabel('Ratio of the Irradiance I2(two rays)/I1(los)')

%               ********* END OF DFAULT VALUES PART ********

elseif st==2;
```

```
%		***********************************************
%		** INPUT VALUES FOR THE MODEL **
%		***********************************************
fx=input('Enter the frequency f in [GHz]:');
htx=input('Enter the Transmitter distance from the wall in [m]:');
hrx=input('Enter the Receiver distance from the Wall in [m]:');
lx1=input('Enter the initial horizontal distance of the reception point in [m]:');
lx2=input('Enter the final horizontal distance of the reception point in [m]:');
count=input('Enter the number of points to calculate between initial and final horizontal
distance:');
if lx1==lx2,
  count=1;
  end;
Eox=input('Enter the value of the Electric field amplitude Eo, at 1m from the source, in [V]:');
nix=input('Enter the refractive index of the air:');
ntx=input('Enter the refractive index of the wall:');

%		***********************************
%		** CREATING THE MODEL **
%		***********************************
f=fx*1E9;
ht=htx;
hr=hrx;
d=linspace(lx1,lx2,count);
Eo=Eox;
ni=nix;
nt=ntx;
eo=8.8542E-12;
c=3E8;
w=2*3.1416*f;
```

```
t=1/w;                          %    evaluated at t=1/w
K=(2*3.1416/3E8)*f;
%        ********************************************
%        ** Geometry considerations for the model **
%        ********************************************
d1=sqrt(((ht-hr)^2)+(d.^2));
d22=sqrt((((ht-hr)^2)+(d.^2)+(4*hr*(ht-hr)))/(((ht/hr)+1)^2));
d21=(ht/hr).*d22;
d2=d21+d22;
a1=K.*d1;
a2=K.*d2;

%        ************************************************************
%        ** Calculating the Incident angle and the Reflectivity Index **
%        ************************************************************
thi=acos(hr./d22);              % incident angle as a function of distance
% NOTE:
% ---------
% We assume horizontal polarization
tht=asin((ni.*sin(thi))./nt);         % Snell's Law
G=(((nt.*cos(thi))-(ni.*cos(tht)))./((ni.*cos(tht))+(nt.*cos(thi))));

%        ****************************
%        ** LOS only (figure 1,2) **
%        ***************************
E1=Eo./d1;                      %   E1 is the amplitude in V/m
E=E1.*sin((w*t)-a1);            %   E  is the magnitude
figure(1);
plot(d,E);
title('T/X - R/X System: LOS - NO Attenuation')
```

```
xlabel('Distance d in [m]')
ylabel('Electric Field E in [V/m]')

I1=0.5*eo*c*(E1.^2);
figure(2);
plot(d,I1);
title('T/X - R/X System: LOS - NO Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')

%           ************************************
%           ** 2-ray path. Reflection (figure 3,4) **
%           ************************************
E2=G.*Eo./d2;
Eot=sqrt((E1.^2)+(E2.^2)+(2.*E1.*E2.*cos(a2-a1)));
a=atan(((E1.*sin(a1))+(E2.*sin(a2)))/((E1.*cos(a1))+(E2.*cos(a2))));
Et=Eot.*sin((w*t)-a);
I2=c*eo*0.5*(Eot.^2);

figure(3)
plot(d,Et);
title('T/X - R/X System: 2-ray path - NO Attenuation')
xlabel('Distance d in (m)')
ylabel('Electric Field E in [V/m]')

figure(4)
plot(d,I2);
title('T/X - R/X System: 2-ray path - NO Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')
```

```
%            ******************************
%            ** Ratio of the Irradiances **
%            ******************************
RI=I2./I1;

figure(5)
plot(d,RI);
title('Ratio of Irradiance. NO Attenuation.')
xlabel('Distance d in (m)')
ylabel('Ratio of the Irradiance I2(two rays)/I1(los)')

end           %    End of the selective loop (default or given values)

%            ****************************
%            ** END OF PROGRAM **
%            ****************************
%-----------------------------------------------------------------
```

B. PROGRAM 2

```
% Ltjg E. D. Kyriakidis
% Hellenic Navy
% --------------------------
%
```

```
%          ***************************************************
%          ** withatre.m - MODEL WITH ATTENUATION **
%          ***************************************************
%
% This program calculates the irradiance I as a function of distance of the reception point, %
for one wave travelling in the Line Of Sight, two rays (one reflected) and their ratio.
% The attenuation factor has been taken into consideration.
%
% Default Values for the problem:
% -------------------------------------
% a) Frequency                                          f = 2.4 GHz
% b) Attenuation                                     A = 0.02E-3 [db/m]
% c) Wall Distance for the transmitter                 ht = 10 m
% d) Wall Distance for the receiver                    hr = 2 m
% e) Permittivity                          eo = 8.8542E-12 Cb2 N-1 m-2
% f) Electric field amplitude in 1m from the source     Eo = 1 V
% g) Speed of light                                c = 3E-8 m/sec
% h) Reflectivity 10%                                   G = 0.1
% i) The distance varies                                2 m - 500 m
% k) For plotting the data pairs are                    3000
%
%------------------------------------------------------------------------

st=input('To run the model with the default values, press 1.
         To give your parameters, press 2:');
if st==1;

%          ***************************************************
%          ** DEFAULT VALUES FOR THE MODEL **
%          ***************************************************
```

```
f=2.4E9;
ht=10;
hr=2;
d=linspace(2,500,3000);
Eo=1;
G=0.1;
A=0.02E-3;
eo=8.8542E-12;
c=3E8;
w=2*3.1416*f;
t=1/w;                          %    evaluated at t=1/w
K=(2*3.1416/3E8)*f;

%          ******************************
%          ** Geometry considerations **
%          ******************************

d1=sqrt(((ht-hr)^2)+(d.^2));
d22=sqrt((((ht-hr)^2)+(d.^2)+(4*hr*(ht-hr)))/(((ht/hr)+1)^2));
d21=(ht/hr).*d22;
d2=d21+d22;
a1=K.*d1;
a2=K.*d2;
S1=exp(-A.*d1);              %    The attenuation of the LOS wave
S2=exp(-A.*d2);              %    The attenuation of the reflected wave

%          ****************************
%          ** LOS only (figure 1,2) **
%          ****************************
E1=Eo.*S1./d1;                  %    E1 is the amplitude in V/m
```

```
E=E1.*sin((w*t)-a1);                % E is the magnitude

figure(1);
plot(d,E);
axis([2 300 -0.14 0.14])
title('T/X - R/X System: LOS - WITH Attenuation')
xlabel('Distance d in [m]')
ylabel('Electric Field E in [V/m]')
I1=0.5*eo*c*(E1.^2);

figure(2);
plot(d,I1);
axis([2 100 0 2E-5]);
title('T/X - R/X System: LOS - WITH Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')

%        ****************************************
%        ** 2-ray path. Reflection (figure 3,4) **
%        ****************************************
E2=G*Eo.*S2./d2;
Eot=sqrt((E1.^2)+(E2.^2)+(2.*E1.*E2.*cos(a2-a1)));
a=atan(((E1.*sin(a1))+(E2.*sin(a2)))/((E1.*cos(a1))+(E2.*cos(a2))));
Et=Eot.*sin((w*t)-a);
I2=c*eo*0.5*(Eot.^2);

figure(3)
plot(d,Et);
axis([2 500 0 0.12])
title('T/X - R/X System: 2-ray path - WITH Attenuation')
```

```
xlabel('Distance d in (m)')
ylabel('Electric Field E in [V/m]')

figure(4)
plot(d,I2);
axis([2 100 0 2.2E-5]);
title('T/X - R/X System: 2-ray path - WITH Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')

%          ******************************
%          ** Ratio of the Irradiances **
%          ******************************
RI=I2./I1;

figure(5)
plot(d,RI);
axis([2 500 0.8 1.22]);
title('Ratio of Irradiance. WITH Attenuation.')
xlabel('Distance d in (m)')
ylabel('Ratio of the Irradiance I2(two rays)/I1(los)')

%     *********** END OF THE DEFAULT VALUES PART *********

elseif st==2;

%          **********************************************
%          ** INPUT VALUES FOR THE MODEL **
%          **********************************************
fx=input('Enter the frequency f in [GHz]:');
```

```
htx=input('Enter the Transmitter distance from the wall in [m]:');
hrx=input('Enter the Receiver distance from the Wall in [m]:');
lx1=input('Enter the initial horizontal distance of the reception point in [m]:');
lx2=input('Enter the final horizontal distance of the reception point in [m]:');
count=input('Enter the number of points to calculate between initial and final horizontal
distance:');
if lx1==lx2,
  count=1;
  end;
Eox=input('Enter the value of the Electric field amplitude Eo, at 1m from the source, in [V]:');
nix=input('Enter the refractive index of the air:');
ntx=input('Enter the refractive index of the wall:');
Ax=input('Enter the attenuation factor in db/m:');

%            **********************************
%            ** CREATING THE MODEL  **
%            **********************************
f=fx*1E9;
ht=htx;
hr=hrx;
d=linspace(lx1,lx2,count);
Eo=Eox;
ni=nix;
nt=ntx;
A=Ax;
eo=8.8542E-12;
c=3E8;
w=2*3.1416*f;
t=1/w;                              % evaluated at t=1/w
K=(2*3.1416/3E8)*f;
```

```
%          *******************************************
%          ** Geometry considerations for the model **
%          *******************************************

d1=sqrt(((ht-hr)^2)+(d.^2));

d22=sqrt((((ht-hr)^2)+(d.^2)+(4*hr*(ht-hr)))/(((ht/hr)+1)^2));
d21=(ht/hr).*d22;
d2=d21+d22;
a1=K.*d1;
a2=K.*d2;
S1=exp(-A.*d1);          %   The attenuation of the LOS wave
S2=exp(-A.*d2);          %   The attenuation of the reflected wave

% ***********************************************************
% ** Calculating the Incident angle and the Reflectivity Index **
% ***********************************************************
thi=acos(hr./d22);        % Incident angle as a function of distance
% NOTE:
% ----------
% We assume horizontal polarization
tht=asin((ni.*sin(thi))./nt);        % Snell's Law
G=(((nt.*cos(thi))-(ni.*cos(tht)))./((ni.*cos(tht))+(nt.*cos(thi))));

%          ***************************
%          ** LOS only (figure 1,2) **
%          ***************************
E1=Eo.*S1./d1;            %  E1 is the amplitude in V/m
E=E1.*sin((w*t)-a1);      %  E  is the magnitude
```

```
figure(1);
plot(d,E);
title('T/X - R/X System: LOS - WITH Attenuation')
xlabel('Distance d in [m]')
ylabel('Electric Field E in [V/m]')

I1=0.5*eo*c*(E1.^2);
figure(2);
plot(d,I1);
title('T/X - R/X System: LOS - WITH Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')

%        ****************************************
%        ** 2-ray path. Reflection (figure 3,4) **
%        ****************************************
E2=G*Eo.*S2./d2;
Eot=sqrt((E1.^2)+(E2.^2)+(2.*E1.*E2.*cos(a2-a1)));
a=atan(((E1.*sin(a1))+(E2.*sin(a2)))/((E1.*cos(a1))+(E2.*cos(a2))));
Et=Eot.*sin((w*t)-a);
I2=c*eo*0.5*(Eot.^2);

figure(3)
plot(d,Et);
title('T/X - R/X System: 2-ray path - WITH Attenuation')
xlabel('Distance d in (m)')
ylabel('Electric Field E in [V/m]')

figure(4)
plot(d,I2);
```

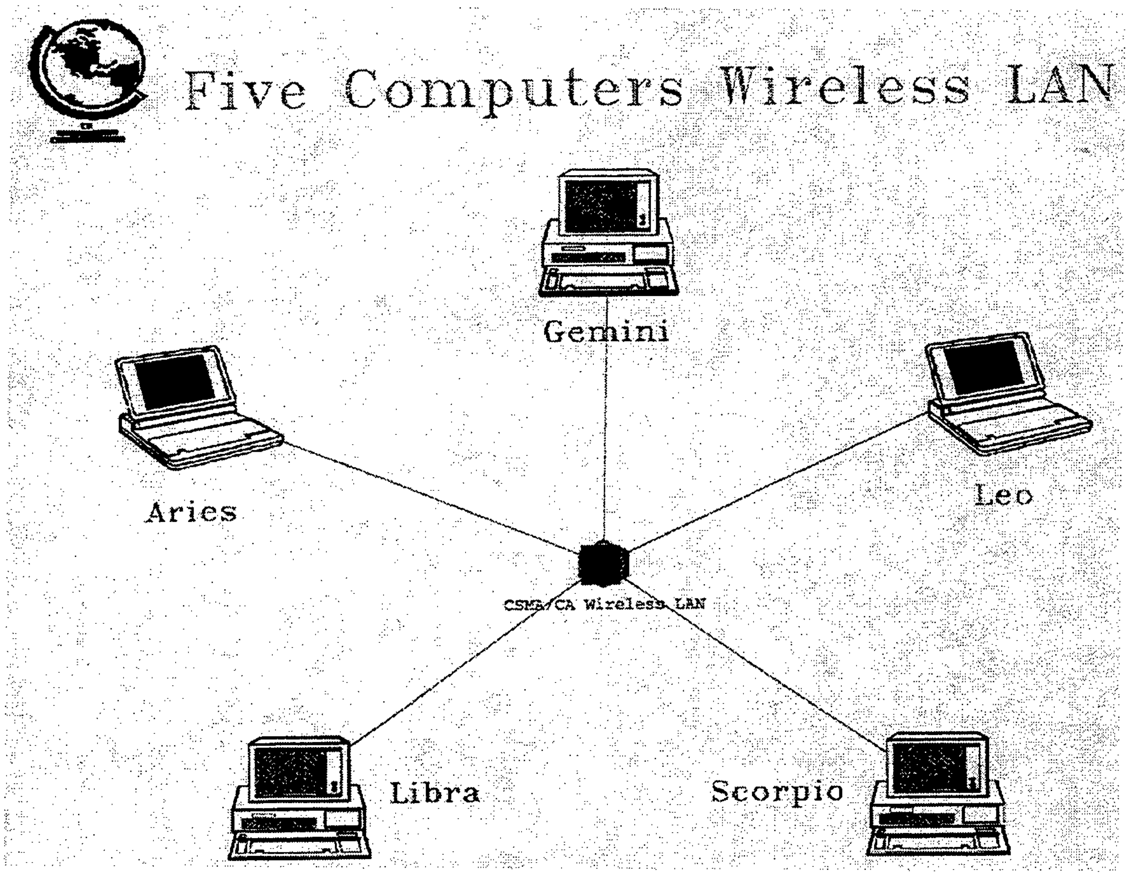
```
title('T/X - R/X System: 2-ray path - WITH Attenuation')
xlabel('Distance d in [m]')
ylabel('Irradiance I in [W/m^2]')
%              ******************************
%              ** Ratio of the Irradiances **
%              ******************************
RI=I2./I1;

figure(5)
plot(d,RI);
title('Ratio of Irradiance. WITH Attenuation.')
xlabel('Distance d in (m)')
ylabel('Ratio of the Irradiance I2(two rays)/I1(los)')

end            % End of selective loop (default or given values)

%              ****************************
%              ** END OF PROGRAM **
%              ****************************
%----------------------------------------------------------------------
```

APPENDIX B. WIRELESS LAN SIMULATION REPORTS



Load: 10 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	629	0	8.762	1.265	22.688	8.8563

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	0
COLLIDED FRAMES	0
NBR OF TRIES TO RESOLVE	
AVERAGE	0.00
STANDARD DEVIATION	0.00
MAXIMUM	0
NBR OF DEFERRALS	59
DEFERRAL DELAY (MS)	
AVERAGE	3.07
STANDARD DEVIATION	2.94
MAXIMUM	14.23
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.00
STANDARD DEVIATION	0.05
MAXIMUM	2
MULTIPLE COLLISION EPISODES	
NBR EPISODES	0
AVG PER EPISODE	0.00
MAX PER EPISODE	0

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL DESTINATION	NUMBER OF PACKETS CREATED	DELIVERED	RESENT	DROPPED	PACKET DELAY (MS) AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	40	40	0	0	9.075	15.913
Aries, Other, Generic Leo	27	27	0	0	8.799	13.704
Aries, Other, Generic Libra	33	33	0	0	8.529	9.763
Aries, Other, Generic Scorpio	25	25	0	0	9.009	16.296
Gemini, Other, Generic Aries	23	23	0	0	9.297	16.785
Gemini, Other, Generic Leo	27	27	0	0	8.804	14.057
Gemini, Other, Generic Libra	30	30	0	0	8.827	13.969
Gemini, Other, Generic Scorpio	33	33	0	0	8.574	10.515
Leo, Other, Generic Aries	32	32	0	0	8.681	11.001
Leo, Other, Generic Gemini	29	29	0	0	9.206	15.882
Leo, Other, Generic Libra	32	32	0	0	8.568	11.419
Leo, Other, Generic Scorpio	29	29	0	0	8.661	13.284
Libra, Other, Generic Aries	52	52	0	0	8.974	19.028
Libra, Other, Generic Gemini	31	31	0	0	9.140	15.774
Libra, Other, Generic Leo	27	27	0	0	9.047	14.178
Libra, Other, Generic						

Scorpio	24	24	0	0	8.621	10.536
Scorpio, Other, Generic Aries	30	30	0	0	9.027	22.688
Scorpio, Other, Generic Gemini	32	32	0	0	8.892	14.778
Scorpio, Other, Generic Leo	43	43	0	0	8.595	13.223
Scorpio, Other, Generic Libra	30	30	0	0	8.476	8.476

Load: 20 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	1164	0	9.238	2.578	32.749	16.39

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	5
COLLIDED FRAMES	10
NBR OF TRIES TO RESOLVE	
AVERAGE	1.00
STANDARD DEVIATION	0.00
MAXIMUM	1
NBR OF DEFERRALS	195
DEFERRAL DELAY (MS)	
AVERAGE	3.92
STANDARD DEVIATION	3.54
MAXIMUM	16.83
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.01
STANDARD DEVIATION	0.12
MAXIMUM	2
MULTIPLE COLLISION EPISODES	
NBR EPISODES	0

AVG PER EPISODE	0.00
MAX PER EPISODE	0

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL	NUMBER OF PACKETS				PACKET DELAY (MS)	
DESTINATION	CREATED	DELIVERED	RESENT	DROPPED	AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	49	49	0	0	9.285	20.712
Aries, Other, Generic Leo	59	59	0	0	10.241	30.193
Aries, Other, Generic Libra	49	49	0	0	9.609	24.442
Aries, Other, Generic Scorpio	54	54	0	0	10.051	32.749
Gemini, Other, Generic Aries	59	59	0	0	9.044	15.097
Gemini, Other, Generic Leo	58	58	0	0	9.776	25.289
Gemini, Other, Generic Libra	56	56	0	0	9.443	24.367
Gemini, Other, Generic Scorpio	56	56	0	0	8.735	15.555
Leo, Other, Generic Aries	59	59	0	0	8.950	19.922
Leo, Other, Generic Gemini	65	65	0	0	9.506	28.567
Leo, Other, Generic Libra	56	56	0	0	9.285	18.580
Leo, Other, Generic Scorpio	55	55	0	0	9.255	31.960
Libra, Other, Generic Aries	65	65	0	0	9.346	23.636
Libra, Other, Generic Gemini	74	74	0	0	9.750	18.232
Libra, Other, Generic						

Leo	69	69	0	0	9.189	18.004
Libra, Other, Generic Scorpio	56	56	0	0	9.431	21.800
Scorpio, Other, Generic Aries	59	59	0	0	9.232	16.560
Scorpio, Other, Generic Gemini	53	53	0	0	9.282	23.199
Scorpio, Other, Generic Leo	53	53	0	0	9.329	30.245
Scorpio, Other, Generic Libra	60	60	0	0	9.237	16.969

Load: 40 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	2439	0	10.811	6.054	83.794	34.34

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	41
COLLIDED FRAMES	83
NBR OF TRIES TO RESOLVE	
AVERAGE	1.17
STANDARD DEVIATION	0.37
MAXIMUM	2
NBR OF DEFERRALS	884
DEFERRAL DELAY (MS)	
AVERAGE	4.78
STANDARD DEVIATION	4.86
MAXIMUM	33.58
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.07
STANDARD DEVIATION	0.29
MAXIMUM	4

MULTIPLE COLLISION EPISODES

NBR EPISODES	1
AVG PER EPISODE	3.00
MAX PER EPISODE	3

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL	NUMBER OF PACKETS				PACKET DELAY (MS)	
DESTINATION	CREATED	DELIVERED	RESENT	DROPPED	AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	133	133	0	0	11.393	59.403
Aries, Other, Generic Leo	126	126	0	0	10.821	57.104
Aries, Other, Generic Libra	120	120	0	0	11.438	64.250
Aries, Other, Generic Scorpio	117	117	0	0	12.467	50.389
Gemini, Other, Generic Aries	139	139	0	0	11.624	73.529
Gemini, Other, Generic Leo	128	128	0	0	11.586	37.811
Gemini, Other, Generic Libra	129	129	0	0	12.069	69.036
Gemini, Other, Generic Scorpio	125	125	0	0	11.289	69.178
Leo, Other, Generic Aries	121	121	0	0	10.890	44.379
Leo, Other, Generic Gemini	122	122	0	0	11.746	65.003
Leo, Other, Generic Libra	109	109	0	0	10.961	48.963
Leo, Other, Generic Scorpio	122	122	0	0	11.497	50.552
Libra, Other, Generic Aries	127	127	0	0	12.617	83.794
Libra, Other, Generic Gemini	129	129	0	0	11.735	46.651

ibra, Other, Generic Leo	110	110	0	0	11.574	50.266
Libra, Other, Generic Scorpio	107	107	0	0	10.687	37.501
Scorpio, Other, Generic Aries	124	124	0	0	11.148	63.182
Scorpio, Other, Generic Gemini	107	107	0	0	10.834	50.907
Scorpio, Other, Generic Leo	110	110	0	0	11.710	45.551
Scorpio, Other, Generic Libra	134	134	0	0	12.313	60.091

Load: 60 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	STD DEV	MAXIMUM	% UTIL
CSMA/CA Wireless LAN	3474	0	13.234	11.314	221.807	48.91

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	125
COLLIDED FRAMES	257
NBR OF TRIES TO RESOLVE	
AVERAGE	1.26
STANDARD DEVIATION	0.54
MAXIMUM	4
NBR OF DEFERRALS	1826
DEFERRAL DELAY (MS)	
AVERAGE	5.89
STANDARD DEVIATION	6.09
MAXIMUM	37.59
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.18
STANDARD DEVIATION	0.47
MAXIMUM	5
MULTIPLE COLLISION EPISODES	
NBR EPISODES	7
AVG PER EPISODE	3.00
MAX PER EPISODE	3

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL DESTINATION	NUMBER OF PACKETS CREATED	DELIVERED	RESENT	DROPPED	PACKET DELAY (MS) AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	164	164	0	0	16.064	226.850
Aries, Other, Generic Leo	171	171	0	0	14.510	78.789
Aries, Other, Generic Libra	190	190	0	0	13.174	102.613
Aries, Other, Generic Scorpio	176	176	0	0	14.186	79.820
Gemini, Other, Generic Aries	178	178	0	0	14.423	163.806
Gemini, Other, Generic Leo	173	173	0	0	14.963	166.328
Gemini, Other, Generic Libra	181	181	0	0	15.502	128.338
Gemini, Other, Generic Scorpio	179	179	0	0	15.633	120.089
Leo, Other, Generic Aries	196	196	0	0	16.799	110.844
Leo, Other, Generic Gemini	156	156	0	0	13.671	65.636
Leo, Other, Generic Libra	187	187	0	0	15.786	118.154
Leo, Other, Generic Scorpio	176	176	0	0	16.303	153.207
Libra, Other, Generic Aries	184	184	0	0	14.559	97.144
Libra, Other, Generic Gemini	138	138	0	0	15.783	117.452
Libra, Other, Generic Leo	162	162	0	0	15.185	92.395
Libra, Other, Generic Scorpio	165	165	0	0	14.789	83.095

Scorpio, Other, Generic Aries	170	170	0	0	16.720	152.950
Scorpio, Other, Generic Gemini	175	175	0	0	15.154	85.829
Scorpio, Other, Generic Leo	181	181	0	0	15.286	107.019
Scorpio, Other, Generic Libra	172	172	0	0	16.530	124.065

Load: 80 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	4696	0	17.608	18.649	242.958	66.12

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	364
COLLIDED FRAMES	743
NBR OF TRIES TO RESOLVE	
AVERAGE	1.30
STANDARD DEVIATION	0.58
MAXIMUM	4
NBR OF DEFERRALS	3306
DEFERRAL DELAY (MS)	
AVERAGE	6.98
STANDARD DEVIATION	7.31
MAXIMUM	48.10
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.38
STANDARD DEVIATION	0.67
MAXIMUM	5
MULTIPLE COLLISION EPISODES	
NBR EPISODES	15
AVG PER EPISODE	3.00
MAX PER EPISODE	3

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL DESTINATION	NUMBER OF PACKETS CREATED	DELIVERED	RESENT	DROPPED	PACKET DELAY (MS) AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	243	243	0	0	25.964	190.952
Aries, Other, Generic Leo	227	227	0	0	23.913	184.629
Aries, Other, Generic Libra	207	207	0	0	22.996	138.368
Aries, Other, Generic Scorpio	246	246	0	0	24.914	175.075
Gemini, Other, Generic Aries	235	235	0	0	26.228	196.026
Gemini, Other, Generic Leo	232	232	0	0	23.476	149.501
Gemini, Other, Generic Libra	227	227	0	0	28.591	205.400
Gemini, Other, Generic Scorpio	259	259	0	0	24.882	182.684
Leo, Other, Generic Aries	211	211	0	0	24.617	145.154
Leo, Other, Generic Gemini	229	229	0	0	22.416	209.277
Leo, Other, Generic Libra	253	253	0	0	28.335	280.821
Leo, Other, Generic Scorpio	242	242	0	0	25.701	202.911
Libra, Other, Generic Aries	260	260	0	0	26.799	232.635
Libra, Other, Generic Gemini	221	221	0	0	28.776	252.256
Libra, Other, Generic Leo	243	243	0	0	28.270	233.036
Libra, Other, Generic Scorpio	214	214	0	0	29.572	242.958

Scorpio, Other, Generic Aries	255	255	0	0	26.838	211.458
Scorpio, Other, Generic Gemini	251	251	0	0	23.495	131.929
Scorpio, Other, Generic Leo	221	221	0	0	21.542	117.540
Scorpio, Other, Generic Libra	220	220	0	0	26.506	204.233

Load: 100 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	5442	0	47.130	79.703	519.812	75.60

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	1418
COLLIDED FRAMES	3042
NBR OF TRIES TO RESOLVE	
AVERAGE	1.58
STANDARD DEVIATION	0.94
MAXIMUM	6
NBR OF DEFERRALS	5262
DEFERRAL DELAY (MS)	
AVERAGE	10.02
STANDARD DEVIATION	9.85
MAXIMUM	51.00
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.88
STANDARD DEVIATION	0.83
MAXIMUM	5
MULTIPLE COLLISION EPISODES	
NBR EPISODES	198
AVG PER EPISODE	3.04
MAX PER EPISODE	4

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL DESTINATION	NUMBER OF PACKETS CREATED	DELIVERED	RESENT	DROPPED	PACKET DELAY (MS) AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	312	296	0	2	1881.070	4482.861
Aries, Other, Generic Leo	309	291	0	1	2039.032	4341.666
Aries, Other, Generic Libra	296	276	0	6	1900.815	4571.266
Aries, Other, Generic Scorpio	295	268	0	4	1923.193	4523.412
Gemini, Other, Generic Aries	257	246	0	5	665.510	2229.361
Gemini, Other, Generic Leo	274	262	0	5	637.097	2001.125
Gemini, Other, Generic Libra	296	280	0	5	699.902	2154.860
Gemini, Other, Generic Scorpio	278	269	0	3	700.566	2234.242
Leo, Other, Generic Aries	280	242	0	4	2686.317	6958.959
Leo, Other, Generic Gemini	283	250	0	4	2737.782	6925.594
Leo, Other, Generic Libra	302	279	0	3	2524.443	7057.435
Leo, Other, Generic Scorpio	274	245	0	3	2525.821	6909.100
Libra, Other, Generic Aries	299	274	0	1	1694.462	5404.633
Libra, Other, Generic Gemini	320	287	0	4	1646.907	5481.629
Libra, Other, Generic Leo	273	253	0	2	1516.713	5302.804

Libra, Other, Generic Scorpio	319	276	0	8	1484.690	5308.394
Scorpio, Other, Generic Aries	271	258	0	3	1183.792	4121.425
Scorpio, Other, Generic Gemini	298	277	0	3	1058.184	4321.407
Scorpio, Other, Generic Leo	311	286	0	3	1108.276	4119.326
Scorpio, Other, Generic Libra	272	254	0	4	1089.298	4289.968

Load: 200 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	5387	0	55.047	86.122	519.889	74.64

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	1720
COLLIDED FRAMES	3647
NBR OF TRIES TO RESOLVE	
AVERAGE	1.66
STANDARD DEVIATION	0.97
MAXIMUM	6
NBR OF DEFERRALS	5375
DEFERRAL DELAY (MS)	
AVERAGE	10.50
STANDARD DEVIATION	9.98
MAXIMUM	51.00
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.94
STANDARD DEVIATION	0.83
MAXIMUM	5
MULTIPLE COLLISION EPISODES	
NBR EPISODES	191
AVG PER EPISODE	3.08
MAX PER EPISODE	4

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL DESTINATION	NUMBER OF PACKETS CREATED	DELIVERED	RESENT	DROPPED	PACKET DELAY (MS) AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	605	255	0	6	14663.531	33444.381
Aries, Other, Generic Leo	599	232	0	1	16657.279	33448.573
Aries, Other, Generic Libra	595	262	0	6	15588.790	33442.132
Aries, Other, Generic Scorpio	583	256	0	9	14836.319	33473.901
Gemini, Other, Generic Aries	599	275	0	5	15601.408	30373.338
Gemini, Other, Generic Leo	585	266	0	3	14464.100	30192.718
Gemini, Other, Generic Libra	566	267	0	2	13481.720	30156.657
Gemini, Other, Generic Scorpio	607	298	0	2	15453.884	30144.994
Leo, Other, Generic Aries	572	253	0	5	15374.280	33447.888
Leo, Other, Generic Gemini	613	268	0	6	15775.048	33394.054
Leo, Other, Generic Libra	589	252	0	3	16524.900	33442.552
Leo, Other, Generic Scorpio	563	237	0	3	14117.889	33435.034
Libra, Other, Generic Aries	621	302	0	6	15555.787	30342.225
Libra, Other, Generic Gemini	545	255	0	2	14899.768	30221.448
Libra, Other, Generic Leo	547	276	0	2	15335.982	30315.158

Libra, Other, Generic Scorpio	641	311	0	5	15088.776	30218.101
Scorpio, Other, Generic Aries	572	257	0	2	17572.425	32770.130
Scorpio, Other, Generic Gemini	575	253	0	9	17879.383	32531.352
Scorpio, Other, Generic Leo	616	253	0	4	18511.292	32835.502
Scorpio, Other, Generic Libra	636	273	0	5	17940.699	32789.916

Load: 400 packets per second

LINKS: CHANNEL UTILIZATION

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK	FRAMES DELIVERED	FRAMES RST/ERR	TRANSMISSION DELAY (MS) AVERAGE	TRANSMISSION DELAY (MS) STD DEV	TRANSMISSION DELAY (MS) MAXIMUM	% UTIL
CSMA/CA Wireless LAN	5427	0	54.908	87.383	520.025	75.16

LINKS: COLLISION STATS

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

LINK NAME	CSMA/CA Wireless LAN
ACCESS PROTOCOL	CSMA/CA
COLLISION EPISODES	1698
COLLIDED FRAMES	3646
NBR OF TRIES TO RESOLVE	
AVERAGE	1.64
STANDARD DEVIATION	0.96
MAXIMUM	6
NBR OF DEFERRALS	5426
DEFERRAL DELAY (MS)	
AVERAGE	10.57
STANDARD DEVIATION	10.05
MAXIMUM	58.27
DEFERRAL QUEUE SIZE (FRAMES)	
AVERAGE	0.96
STANDARD DEVIATION	0.83
MAXIMUM	5
MULTIPLE COLLISION EPISODES	
NBR EPISODES	240
AVG PER EPISODE	3.04

MAX PER EPISODE 4

BACKGROUND PACKET FLOWS: PACKET DELAY

REPLICATION 1 FROM 0.0 TO 60.0 SECONDS

ORIGIN, APP, PROTOCOL DESTINATION	NUMBER OF PACKETS CREATED	DELIVERED	RESENT	DROPPED	PACKET DELAY (MS) AVERAGE	MAXIMUM
Aries, Other, Generic Gemini	1189	252	0	4	21121.788	46508.969
Aries, Other, Generic Leo	1170	209	0	4	25171.833	45990.465
Aries, Other, Generic Libra	1217	261	0	8	23567.941	46641.934
Aries, Other, Generic Scorpio	1113	241	0	6	21949.355	46646.181
Gemini, Other, Generic Aries	1194	255	0	5	24627.327	46191.546
Gemini, Other, Generic Leo	1165	267	0	5	22530.895	46095.140
Gemini, Other, Generic Libra	1165	266	0	9	22805.035	46190.646
Gemini, Other, Generic Scorpio	1222	274	0	5	22862.945	46155.722
Leo, Other, Generic Aries	1224	272	0	2	21340.311	44242.994
Leo, Other, Generic Gemini	1175	255	0	6	21615.989	44569.200
Leo, Other, Generic Libra	1221	294	0	4	21055.837	44348.358
Leo, Other, Generic Scorpio	1169	275	0	5	23163.882	44626.421
Libra, Other, Generic Aries	1204	299	0	4	22378.812	44799.735
Libra, Other, Generic Gemini	1248	309	0	3	22243.530	44678.902
Libra, Other, Generic Leo	1166	280	0	0	22683.393	44685.758

Libra, Other, Generic Scorpio	1230	303	0	5	22256.234	44594.762
Scorpio, Other, Generic Aries	1165	254	0	3	23072.067	45526.785
Scorpio, Other, Generic Gemini	1128	263	0	5	21939.085	44555.563
Scorpio, Other, Generic Leo	1172	245	0	3	21751.129	44573.810
Scorpio, Other, Generic Libra	1206	264	0	3	21030.446	45180.268

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